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VKM Report 2021: 19

Assessment of treatment methods and validation criteria for composting and biogas facilities in relation to plant health risks and the risk of spreading alien organisms

Scientific Opinion of the Panel on Plant Health of the Norwegian Scientific Committee for Food and Environment

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Preparation of the opinion

The Norwegian Scientific Committee for Food and Environment (Vitenskapskomiteen format og miljø, VKM) appointed a project group to draft the opinion. The project group consisted of four VKM members and one project manager from the VKM staff. Two external referees commented on and reviewed the draft opinion. The Panel on Plant Health evaluated and approved the final opinion.

Authors of the opinion

The authors have contributed to the opinion in a way that fulfils the authorship principles of VKM (VKM, 2019). The principles reflect the collaborative nature of the work, and the authors have contributed as members of the project group and/or the VKM Panel on Plant Health.

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emphasises that the referees are not responsible for the content of the final opinion. In accordance with VKM's routines for approval of a risk assessment (VKM, 2018), VKM received their comments before evaluation and approval by VKM Panel on Plant Health and before the opinion was finalised for publication.

Competence of VKM experts

Persons working for VKM, either as appointed members of the Committee or as external experts, do this by virtue of their scientific expertise, not as representatives for their employers or third-party interests. The Civil Services Act instructions on legal competence apply for all work prepared by VKM.

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Summary

Key words: VKM, risk assessment, Norwegian Scientific Committee for Food and Environment, Norwegian Food Safety Authority, Norwegian Environment Agency, Biowaste, Compost, Plant health, organic waste, Phytosanitary safety, Biogas, Alien organisms

Introduction

The Norwegian Food Safety Authority (NFSA) and the Norwegian Environment Agency (NEA) have jointly asked the Norwegian Scientific Committee for food and environment for an assessment into treatment methods and validation methods for compost and digestate based on organic waste in relation to plant health and the spread of harmful alien organisms in Norway.

The Norwegian Food Safety Authority will use the report in its supervisory work over companies that produce compost and digestate. The assessment will also provide important input for the regulatory development of several current regulations including regulations on indicator organisms that are used to validate new methods and ensure adequate security with regards to the survival of plant pests.

The Norwegian Environment Agency wants to establish whether the methods used in the composting of garden waste and other types of plant waste today are able to ensure that the finished product does not become a source for the spread of harmful alien organisms. This will form the basis for the Norwegian Environment Agency's guidelines relating to the precautionary provisions in the regulation on alien organisms.
This request is limited to an assessment of plant pests and harmful alien organisms (hereinafter alien organisms). The survival of infectious diseases harmful to people and animals is considered in separate assessments.

Methods

We have conducted initiating workshops for identifying relevant fundamental processes and parameters, of relevant organisms and of relevant search terms for the literature surveys, as well as for discussion and validation. Visits to composting facilities and contact with stakeholders in Norway were also conducted. This information was further implemented in an extensive literature search.

This assessment include/encompass organic waste and other materials that are currently treated in biogas and composting facilities, including garden and park waste (incl. soil), plant waste from garden centres, etc., food waste and waste from the food and animal feed industry (including grain/seed husks and waste from enterprises which package and process potatoes and vegetables), manure, bulking agents used in composting facilities, and husks from contracted grain/seed cleaners for sowing.

We have used a quantitative risk assessment. The level of confidence in the risk assessment is described, and uncertainties and data gaps identified.

Furthermore, we have used re-submission commenting and external expert reviewing before final approval and publication.

Results and conclusions

Adequacy of critical operating conditions often used in the sanitation stage of composting and biogas facilities in Norway for prevention of plant pests dispersal: Absence of alien organisms in the feedstock entering composting and biogas facilities or appropriate pre-treatment of feedstock are of high priority to avoid the dispersal of alien organisms. For compost facilities, no general conclusion on the number of turnings of a windrow or mattress and on the division into phases can be drawn due to the diverse process and facility conditions, as well as constraints in accurate monitoring of process variables. Pre-treatment of material of a particle size of 12 mm at 70 °C for 60 min will free the material from most quarantine pests, except root-knot nematodes (*Meloidogyne* spp.) and potato wart disease (*Synchytrium endobioticum).* The decisive factor, *i.e.,* infectivity and reproduction, still remains to be investigated for many quarantine pests. Potato cyst nematodes and root knot nematodes are expected to withstand both aerobic mesophilic fermentation and anaerobic mesophilic digestion as well as vermicompost processes and basket composting. Root knot nematodes could survive anaerobic digestion with hydrolysis/acidogenesis, anaerobic digestion with thermophilic acetogenesis/methanogenesis. With regard to composting in actively and passively aerated piles, survival rates depend on the temperature reached and duration of high temperature conditions.

Validity of validation methods for hygienic safety for phytosanitary purposes: The feedstock materials in focus are either not recruited from hygienically questionable sources and/or have already been approved for human consumption (food wastes). The presence of the three target organisms *Salmonella* Senftenberg (775W, H_2S-negative), *Enterococcus faecalis* and eggs of *Ascaris suum* in the feedstock is unlikely. Spiking of feedstock with human pathogens are not recommended. Given the deviating cardinal levels for decisive parameters for alien organisms, it is unlikely that these organisms and structures are suitable for validation.

Probability for dispersal of harmful alien organisms from composting and biogas facilities: With a few exceptions, there is no reason to assume that harmful alien organisms can establish themselves in new areas if they are spread from composting and biogas facilities, unless host plants or favorable natural environments are present. Spread and establishment of harmful alien organisms is likely with a low uncertainty from feedstock that only has been exposed to mesophilic conditions. However, spread and establishment of alien organisms from digestates subjected to a pre- or post-process high temperature-high

pressure hygienisation step (minimum temperature: 133 °C, pressure: 3 bar, exposure time: 20 min) is unlikely with a low uncertainty.

Harmful alien organisms that may result in highly negative consequences if spread from composting and biogas facilities: Japanese knotweed (*Reynoutria japonica)*, onion white rot (*Sclerotium cepivorum*,) potato wart disease (*Synchytrium endobioticum)*, potato cyst nemtodes (*Globodera rostochiensis* and *G. pallida)*, root-knot nematodes (*Meloidogyne chitwoodi* and *M. fallax*) are identified as harmful alien organisms that may result in highly negative consequences if they are spread.

Relevant risk-reducing measures considering effectiveness and feasibility: There is no such "magic" indicator organism that mimics the response of all undesired organisms during anaerobic and aerobic degradation. Heavily contaminated material should be avoided entering any of the assessed processes. To account for survival of the hardiest pests and pathogens, pre- and post-process treatments may be added on the different modes of organic matter transformation, especially with regard to anaerobic digestion. Common pre-process treatments aim at feedstock disintegration and use physical (thermal: low or high temperature treatment, microwave treatment; mechanical; electrical), chemical (acid hydrolysis, alkaline hydrolysis, thermal-chemical wet oxidation; activated wet oxidation) and biological/biochemical techniques (addition of microorganisms or enzymes).

In contrast to composting, organic matter retrieved from anaerobic digestion (AD) may be subjected to a thermal post-process treatment at either low (minimum temperature: 70 °C; exposure time:1 h) or high temperature and high pressure (minimum temperature: 133 °C, pressure: 3 bar; exposure time: 20 min), respectively.

Organisms that may pose a risk are associated with wasted potato and onion. Compost containing material from gardens and parks would pose no plant health risks if it has been appropriately pre-treated with heat, or if the compost has been treated during maturation. Without pre- or post-treatments, such material might pose plant health risks if used in agriculture and horticulture.

Sammendrag på norsk

Nøkkelord: VKM, risikovurdering, Vitenskapskomiteen for mat og miljø, Mattilsynet, Miljødirektoratet, biorest, kompost, plantehelse, organisk avfall, plantesanitære forhold, biogass, fremmede organismer

Introduksjon

Mattilsynet og Miljødirektoratet har bedt Vitenskapskomiteen for mat og miljø om en vurdering av behandlingsmetoder og valideringsmetoder for kompost og biorest basert på organisk avfall med hensyn til risiko for plantehelse og spredning av skadelige, fremmede organismer i Norge.

Mattilsynet vil bruke rapporten i sitt tilsynsarbeid overfor virksomheter som produserer kompost og biorest. Vurderingen vil også være et viktig kunnskapsgrunnlag for å vurdere om indikatororganismer som benyttes til å validere nye metoder gir tilstrekkelig sikkerhet når det gjelder overlevelse av planteskadegjørere, og vil gi viktige innspill til regelverksutvikling for flere av de aktuelle forskriftene.

Miljødirektoratet ønsker svar på om metodene som brukes til kompostering av hageavfall og andre typer planteavfall i dag sikrer at det ferdige produktet ikke er en kilde til spredning av skadelige, fremmede organismer. Dette vil danne grunnlaget for Miljødirektoratets veiledning knyttet til aktsomhetsbestemmelsene i forskrift om fremmede organismer.

Oppdraget er avgrenset til en vurdering av planteskadegjørere og skadelige, fremmede organismer (heretter fremmede organismer). Spørsmål knyttet til overlevelse av smittsomme sykdommer som er skadelige for mennesker og dyr blir behandlet i egne vurderinger.

Metoder

VKM har identifisert relevante organismer, prosesser og parametere gjennom workshops og diskusjoner. VKM har også besøkt komposteringsanlegg og vært i kontakt med interessenter i Norge. Denne informasjonen ble lagt til grunn for et omfattende litteratursøk.

Vurderingen omfatter organisk avfall og andre materialer som i dag behandles i biogass- og komposteringsanlegg. Dette innbefatter hage- og parkavfall (inkl. jord), planteavfall fra hagesentre o.l., matavfall og avfall fra fôr og næringsmiddelindustrien (inkludert korn- og frøavrens og avfall fra virksomheter som pakker og bearbeider poteter og grønnsaker), husdyrgjødsel, strukturmaterialer som brukes i komposteringsanlegg, samt avrens fra leierenserier for såvarer.

VKM har gjort en kvalitativ risikovurdering. Styrken på kunnskapen som ligger til grunn for risikovurderingen er beskrevet, og usikkerhet og kunnskapshull er identifisert. Eksterne eksperter har gjennomgått og kommentert vurderingen før endelig godkjenning og publisering.

Resultater og konklusjoner

Vurdering av om de vanligste hygieniseringsmetodene som benyttes i komposterings- og biogassanlegg i Norge i dag er tilstrekkelige til å forhindre spredning av planteskadegjørere og fremmede organismer:

Det er svært viktig atråstoffet som kommer inn til komposterings- og biogassanlegg ikke inneholder fremmede organismer, og at råstoffet er hensiktsmessig/adekvat forbehandlet.

Når det gjelder kompostanlegg kan det ikke trekkes noen generell konklusjon med hensyn til antall vendinger av en ranke eller madrass og inndeling i faser. Det er på grunn av store ulikheter i prosess- og anleggsforholdene, og begrensninger i overvåkingen av prosessvariabler.

Med unntak for rotgallnematoder (*Meloidogyne* spp.) og potetkreft (*Synchytrium endobioticum*) vil en forbehandling av materiell med partikkelstørrelse på 12 mm ved 70 ° C i 60 minutter resultere i at de fleste karanteneskadegjørere ikke vil overleve. Når det gjelder avgjørende faktorer som smitteevne og reproduksjon, er dette ikke undersøkt for mange av karanteneskadegjørerne.

Potetcystenematoder og rotgallnematoder forventes å tåle både aerob og anaerob mesofil nedbryting, så vel som vermikompostering og hjemmekompostering.
Rotgallnematoder vil kunne overleve anaerob nedbryting med mesofil hydrolyse/acidogenese og anaerob nedbryting med termofil acetogenese/metanogenese.
Når det gjelder kompostering i aktivt og passivt luftede hauger, vil overlevelsesraten avhenge av både oppnådd temperatur og hvor lenge de høye temperaturforholdene varer.

Vurdering av validitet/gyldighet av valideringsmetoder for hygienisk sikkerhet for plantesanitære formål:

Råstoffet som er vurdert i denne rapporten, er enten ikke hentet fra hygienisk problematiske kilder og/eller de er allerede godkjent for humant konsum (matavfall). VKM vurderer at tilstedeværelse/forekomst av de tre målorganismene *Salmonella* Senftenberg (775W, H2S-negativ), *Enterococcus faecalis*, og egg av *Ascaris suum* i råstoffet er usannsynlig.

Sannsynlighet for spredning av skadelige fremmede organismer fra komposterings- og biogassanlegg:

Med noen få unntak er det ikke grunn til å anta at skadelige, fremmede organismer vil etablere seg i nye områder dersom de spres fra komposterings- og biogassanlegg, med mindre aktuelle vertsplanter eller gunstige miljøbetingelser er til stede. Når det gjelder råstoff som kun har vært utsatt for mesofile forhold, vurderer VKM at spredning og etablering av skadelige fremmede organismer er sannsynlig, med lav usikkerhet.

For råstoff som har vært utsatt for et høytemperatur-høytrykks-hygieniseringstrinn før eller etter prosess (minimumstemperatur: 133 °C, trykk: 3 bar, eksponeringstid: 20 minutter), vurderer VKM at sannsynligheten for spredning og etablering av fremmede organismer er usannsynlig, med en lav usikkerhet.

Skadelige fremmede organismer som kan gi svært negative konsekvenser ved spredning fra komposterings- og biogassanlegg:
Parkslirekne (*Reynoutria japonica*), løkhvitråte (*Sclerotium cepivorum*), potetkreft (*Synchytrium endobioticum*), gul potetcystenematode (*Globodera rostochiensis*), hvit potetcystenematode (*G. pallida*) og rotgallnematoder (*Meloidogyne chitwoodi* og *M. fallax*) er identifisert som skadelige, fremmede organismer som kan ha svært negative konsekvenser hvis de spres**.**

Relevante risikoreduserende tiltak med tanke på effektivitet og gjennomførbarhet:
Det finnes ingen "magisk" indikatororganisme som etterligner responsen til alle uønskede organismer under anaerob og aerob nedbrytning. Generelt bør man unngå at materialer som er sterkt forurenset kommer inn i prosessene som er vurdert. For å ta hensyn til overlevelsen av de alvorligste skadegjørerne og patogenene, kan før og etter(prosess)behandlinger legges til på de forskjellige metodene for transformasjon av organisk materiale, spesielt med hensyn til anaerob nedbryting.

Vanlige forprosessbehandlinger har som formål å bryte ned råstoffet ved fysiske (termisk: lav- eller høytemperaturbehandling, mikrobølgebehandling; mekanisk; elektrisk), kjemisk (syrehydrolyse, alkalisk hydrolyse, termisk-kjemisk våtoksidasjon; aktivert våtoksidasjon) og biologisk/ biokjemiske teknikker (tilsetning av mikroorganismer eller enzymer).

I motsetning til kompostering, kan organisk materiale fra anaerob nedbrytning (AD) utsettes for en termisk etterbehandling enten ved lav (minimumstemperatur: 70 °C; eksponeringstid: 1 time) eller høy temperatur og høyt trykk (minimumstemperatur: 133 °C, trykk: 3 bar, eksponeringstid: 20 min).

Organismer som kan utgjøre en risiko er forbundet med innhold av potet og løk i de ulike avfallstypene. Kompost som inneholder materiale fra hager og parker vil ikke utgjøre noen plantehelserisiko hvis den har blitt forbehandlet på riktig måte med varme, eller hvis komposten har blitt behandlet under modning. Uten for- eller etterbehandling kan slikt materiale utgjøre en plantehelserisiko hvis det brukes i jord- og hagebruk.

Abbreviations and glossary

Abbreviations

AD	Anaerobic digestion
MAD	Mesophilic anaerobic digestion

Glossary

Term	Definition	Reference
Aerobic	Organism/process requiring "presence of oxygen (O_2); may be either facultative, obligate aerobic or microaerophilic	(Madigan et al., 2015)
Alien organism	Harmful alien organism Alt.1_An organism spread, intentionally or unintentionally, through human activities to areas where they do not naturally occur. Alt 2_Alien Species (IUCN definition): a species, sub-species, or lower taxon occurring outside of its natural range (past or present) and dispersal potential (i.e. outside the range it occupies naturally or could not occupy without direct or indirect introduction or care by humans) and includes any part, gametes or propagule of such species that might survive and subsequently reproduce.	
Anaerobic	Organism/process requiring "absence of oxygen (O_2); may be either obligate or strict anaerobic	(Madigan et al., 2015)

Term	Definition	Reference
Compost	Biologically stabilized solid material retrieved from an aerobic degradation process consisting of multiple thermal phases (mesophilic, thermophilic, mesophilic) accompanied by a succession in microbial community structure In the present report the term compost describes either … (scenario 1) or … (scenario 2) according to the terms of references 1a and 1b.NB! Misleadingly, some authors use the term "compost" synonymous to growing medium or plant substrate. However, this is not the matter in this report.	
Compost tea	Liquid extract retrieved during decomposition of organic matter under aerobic conditions (composting)	
Digestate	A by-product of the anaerobic digestion process which can be used in liquid form as an effective biofertiliser recycling nutrients back to land, and in solid (fibre, or cake) form as a soil conditioner	(Henry et al., 2013)
Desinfection	"Elimination of pathogens from inanimate objects or surfaces"	(Madigan et al., 2015)
Eradication	Control of plant disease by eliminating the pathogen after it is established or by eliminating the plants that carry the pathogen	(Agrios, 2005)
Elimination	Removal	
Fermentation	"Anaerobic catabolism of an organic compound in which the compound serves both as an electron donor and electron acceptor and in which ATP is usually produced by substrate-level phosphorylation"	(Madigan et al., 2015)
Growing medium	Medium replacing soil in soilless culture (also called plant substrate)	
Hygienization		
Inactivation	Destruction or removal of activity	
Indicator organisms	"…a group or species indicative of pathogen presence and behavior, respectively,…"	(Gerba, 2009)

Term	Definition	Reference
Inoculum	The pathogen or its parts that can cause infection; that portion of individual pathogens that are brought into contact with the host	(Agrios, 2005)
Kill	Completely destroy an organism's metabolic activity	
Pasteurization	"Use of controlled heat to reduce the microbial load, including both pathogens and spoilage organisms in heat-sensitive liquids"	(Madigan et al., 2015)
Sanitation	Process leading to "reduce, but not eliminate, microbial cells to a safe level"	(Madigan et al., 2015)
Soil conditioner	"…substance that improves the physical properties of soil"	(Wallace, 2020)
Suppression	Impaired establishment of an organisms or establishment but impaired disease establishment due to abiotic or biotic environmental conditions	

Background as provided by the Norwegian Food Safety Authority and the Norwegian Environment Agency

The Norwegian Food Safety Authority and the Norwegian Environment Agency are jointly commissioning an assessment into treatment methods and validation methods for compost and digestate based on organic waste in relation to plant health and the spread of harmful alien organisms in Norway.

Background

The circular economy should encourage the protection and best possible use of resources. Using organic waste as a fertilizer and soil conditioner ensures that nutrients and organic materials in the waste can be put to good use. Treating the waste in a biogas facility also makes it possible to use the energy in such waste. In Norway, a large quantity of organic waste is treated in biogas and composting facilities. According to Statistics Norway (SSB), approximately 80% of all garden and park waste collected in Norway was sent for composting in 2016. In the case of food waste and organic waste from the food industry, close to 50% was treated in biogas facilities while just over 20% was sent for composting in the same year. Compost is used primarily in green spaces and gardens while a large proportion of digestate is used in agriculture.

The reuse of resources found in waste is a development that is being stimulated at several levels. In 2018, the EU adopted a new regulation for the CE-marking of fertilizer products in an effort to promote the circular economy[1]. White paper no. 45 (2016–2017: Waste as Resource – Waste Policies and the Circular Economy)[2] also considers "the need to use resources as effectively as possible, for example by composting organic waste and using it to replace peat in soil products, or by treating food waste in biogas facilities in order to turn it into a high-grade fertilizer that can replace mineral fertilizers". In Norway, a proposal is currently being discussed to phase out the use of peat in growing media[3] – a measure which could also lead to an increased use of compost and digestate in growing media and soil conditioners.

It is important to ensure that waste used in the production of compost and digestate is treated in an adequate manner, so as to ensure that the products are free of infectious diseases, alien organisms and other undesired organisms.

Most of the alien organisms we have in Norway are vascular plants and many of these are also known garden plants. These can spread through the environment and negatively impact biodiversity. It is known that garden waste can lead to the spreading of alien organisms whenever it is disposed of at illegal waste dumping sites. It is therefore important to have knowledge on good and safe methods on how to transform garden waste containing alien organisms into compost that does not contribute further to the spread of such organisms.

Waste from garden centres and other retail outlets selling plants can also contribute to the spread of alien organisms if the waste is not treated adequately.

This request is limited to an assessment of plant pests and harmful alien organisms (hereinafter alien organisms). The survival of infectious diseases harmful to people and animals is considered in separate assessments. Alien organisms can be spread by many different types of organic waste. This can include organisms which are already found in Norway or organisms which are brought in via the import of garden plants or food, for example. In the case of garden waste this can also include soil-dwelling organisms as studies have shown that garden waste contains a considerable proportion of soil[4]. Chopped wood, such as wooden pallets, is sometimes used as structural materials in composting facilities. It is also known that imported wood packaging can carry undesired organisms[5].

Current regulations

The regulation on alien organisms does not stipulate any requirements for a permit to treat garden waste however the fifth chapter of this regulation does make it a requirement to take precautions in connection with any and all activities that may lead to the unintended spread of alien organisms.

The regulation on fertiliser products regulates plant health risks in fertilizer products which are produced, imported and sold in Norway. According to this regulation it is a requirement that the product must not constitute a risk to plant, animal or human health through its use. Products and their use – including possible misuse – must not entail the risk of spreading infectious diseases to humans, animals or plants. The regulation therefore establishes a requirement that the product must not transmit any diseases but it does not specify how this should be achieved. It is up to the enterprises themselves to treat the materials in such a way that ensures they are free from infectious diseases. Individual enterprises can document their own processes themselves or the industry can come together and establish common industry methods. This has been the case for the windrow composting of animal byproducts (Avfall Norge) and the composting of garden waste (Avfall Norge)[6]. A number of the raw materials that are to be assessed in this order are animal byproducts or materials which are processed together with animal byproducts and therefore processed in accordance with the regulation on animal byproducts. This regulation has its own standard methods for the treatment of different materials but is also open to other methods provided that a further specified validation methodology can demonstrate that the treatment method in question is adequate. The common denominator for all of the methods in the regulation on animal byproducts is that they have not (or only to a limited extent) been assessed to ensure they are adequate in relation to plant health risks.

The regulation on fertilizer products is currently under review and a draft for the coming regulation suggests that a clearer requirement should be introduced in relation to the validation of methods. The proposal suggests that new treatment methods should be required to undergo a validation process which demonstrates that the infectious eggs of *Ascaris suum* cannot survive and that a $5\log_{10}$ inactivation of

Salmonella Senftenberg (775W, H_2S-negative) is achieved. This methodology is used today for both sewage sludge and animal biproducts but there is a lack of knowledge around how the validation method functions in relation to assessing plant health risks.

According to the regulation on wild oats, it is forbidden to sell grain/seed husks and manure from a property where there are wild oats with the exception of products that are treated so that the germination capacity of any wild oats has been destroyed or which are sold to companies that will destroy the germination capacity of the wild oats as part of their continued processing. The same applies to husks and waste from facilities that take in grains, peas or seeds (such as contracted grain/seed cleaners). Wild oats could potentially be spread by certain raw materials that are processed in biogas and composting facilities such as grain husks from mills or manure[7]. The regulation on plant health sets forth a general prohibition against spreading quarantine pests and establishes a requirement that the site of production for organic growing media must be free from specified plant pests.

About the assessment

The Norwegian Food Safety Authority will use the report in its supervisory work over companies that produce compost and digestate. The assessment will also provide important input for the regulatory development of several current regulations including regulations on indicator organisms that are used to validate new methods and ensure adequate security with regards to the survival of plant pests.

The Norwegian Environment Agency wants to establish whether the methods used in the composting of garden waste and other types of plant waste today are able to ensure that the finished product does not become a source for the spread of harmful alien organisms. This will form the basis for the Norwegian Environment Agency's guidelines relating to the precautionary provisions in the regulation on alien organisms.

The assessment must encompass organic waste and other materials that are currently treated in biogas and composting facilities, including:

- Garden and park waste (incl. soil)
- Plant waste from garden centres, etc.
- Food waste and waste from the food and animal feed industry (including grain/seed husks and waste from enterprises which package and process potatoes and vegetables[8])
- Manure
- Bulking agents used in composting facilities
- Husks from contracted grain/seed cleaners for sowing

Terms of reference as provided by the Norwegian Food Safety Authority and the Norwegian Environment Agency

1. Assess whether critical operating conditions which are often used in the sanitation stage of composting and biogas facilities is adequate in order to prevent the spreading of plant pests (including viable plant parts and seeds) and harmful alien organisms (hereinafter alien organisms).
    1.1 Composting in windrows (> 2.5m) or mattresses where the temperature of the windrow is at least 55 °C for four weeks and the windrow is turned at least three times during this period.
        1.1.1 Also assess a variation of this whereby sanitation is divided into four periods with a temperature of at least 55 °C for at least one week, but where there can be intervals between each of these periods during which temperature is not measured. The material must be turned between each of these four periods.
    1.2. Treatment at 70 °C for 60 minutes with a max particle size of 12 mm whereby this is achieved in a composting process or as a pretreatment step before an anaerobic treatment process.
2. If the treatment facility uses other sanitation methods than those listed in point one: Assess
    whether the following validation methodology is appropriate in order to ensure that the sanitation method being used is adequate in order to prevent the spread of alien organisms in compost and digestate:
    2.1. 5log10 inactivation of *Salmonella* Senftenberg (775W, H_2S-negative)
    2.2 5log10 inactivation of *Enterococcus faecalis*
    2.3 tests showing that the content of infective eggs from the indicator organism *Ascaris suum* has been reduced to zero.
    2.4 Assess whether alternative indicator organisms other than those mentioned in points 2a to 2c could better describe the probability of alien organisms not surviving.
3. Assess the probability that harmful alien organisms will spread further from composting and
    biogas facilities if the waste is treated in accordance with the requirements set out in points
    one or two.
4. Identify harmful alien organisms that may result in highly negative consequences if they are
    spread from composting and biogas facilities.
5. Identify relevant risk-reducing measures and evaluate their effectiveness and feasibility.

Methodology and Data

The assessment was based on an iterative process, consisting of

a. Site visits at Norwegian waste companies using composting and anaerobic digestions (AD)
    a. Workshops for identify relevant fundamental processes and parameters, of relevant organisms and of relevant search terms for literature surveys, as well as for discussion and validation
    b. Literature survey
    c. Individual writing sessions
    d. Pre-submission commenting and external expert review.

The assessment was conducted during the Covid-sars-2 pandemic; therefore, all joint work was conducted by virtual meetings.

Data and information gathering

During the summer of 2020 two different composting facilities in the Oslo area was visited. Unfortunately, and most solidly due to the covid-19 situation and regulation, no other composting nor any biogas facilities were visited.

Ratings of probabilities and uncertainties

All probabilities in the different steps of the pathway were rated separately. The ratings were qualitative and followed a fixed scale: unlikely, moderately likely, likely.
For the conclusions on probabilities (as described above), the levels of uncertainty were rated separately. The ratings were quantitative and followed a fixed scale: low, medium, high.
The description of each rating is given in Appendix I of the current opinion.

Literature search and selection

The current assessment covers a broad spectrum of organisms affecting the environment and the health of plants, humans and animals (Appendix II). These organisms vary substantially in morphological and physiological properties. The choice of relevant organisms was therefore based on the process properties related to anaerobic digestions (AD) and composting (see also figure 1 and 2) and selection of relevant organisms based on their capacity to resist heat as well as on their potential to substantially and adversely affect plant health or have environmental effects on predominantly horticultural and agricultural crops. Selected organisms comprise the hardiest species; thus, not all potential organisms have been individually evaluated (e.g., TobamoVirus covers all relevant viruses). The selected model organisms based on these criteria are listed in Table 1. In addition to literature surveys, the compilation of the list was guided by reviews by Noble and Roberts (2004) and Witchuk et al. (2011), as well as by specific recommendations of the Norwegian Food Safety Authority.
The literature survey followed the recommendations developed for systematic reviews and meta-analyses (Moher et al., 2009) (Appendix II) and covered literature without time limitation including English, German, French and Scandinavian literature based on original

data publications in scientific peer-reviewed journals, reports as well as conference proceedings. "Composting", "Anaerobic digestion", "Anaerobic fermentation" and "Thermal inactivation" served as key concepts. Current binomials, synonyms, previous Latin binomials and common English names of selected unwanted organisms were included as keywords into the individual searches (Table 2). All keywords and keyword combinations are listed in Appendix II. The general and specific inclusion and exclusion criteria are presented in Table 3. The literature search was conducted during April 20 through July 19, 2021. Searches were performed in Web of Science (WoS) using all WoS databases (Web of Science Core Collection, Biosis Citation Index, CABI, Current Contents Connect, Data Citation Index, Derwent Innovation Index, KCI-Korean Journal Database, MEDLINE, Russian Science Citation Index, SciELO Citation Index, Zoological Record).

In addition, forward and backward searches were performed on top of less recent, but central articles. A few, additional articles were found in the reference lists of the review articles that had been identified in the initial searches.

Table 1. Model organisms selected for the present assessment, their current and previous binominal names, as well as English and Norwegian common names of diseases or organisms and range of host plants or material, as mentioned in the background provided by NFSA and NEA.

Organism (current binomial name)	**Previous binomial names, synonyms**	**English common name/name of disease**	**Norwegian common name/ name of disease**	**Range of host plants and material**
Slug				
Arion vulgaris		Spanish slug	Brunskogsnegl Iberiaskogsneg	*Allium cepa, A. sativum*, *Armoracia lapathifolia*, *Beta vulgaris* var. *conditiva*; various *Brassica oleracea* species, *Capsicum annuum*, various *Cucumis* and *Curcurbita* species, *Daucus carota*, *Lactuca sativus*, *Petroselium crispum*, *Solanum lycopersicium,* various *Phaseolus vulgaris*, varieties *Pisum sativum*, *Raphanus sativus*, *Vicia faba*, *Zea mays*
Insects				
Leptinotarsa decemlineata		Colorado potato beetle	Koloradobille	Various wild and breeded species within Solanaceae, e.g., *Solanum tuberosum*, *S. lycopersicium*,
Popillia japonica		Japanese beetle	Japanbille	Shrubs and trees

Organism (current binomial name)	Previous binomial names, synonyms	English common name/name of disease	Norwegian common name/ name of disease	Range of host plants and material
Anoplophora glabripennis		Asian long-horned beetle, sky beetle, Starry sky beetle, ALB	Asiatisk løvtrebukk	Broad host range among these *Acer*, *Asparagus officinalis*, *Glycine max*, *Rheum hybridum*, various species within Rosaceae, *Tilia*, *Ulmus*
Nematodes				
Meloidogyne spp.		Root-knot nematodes	Rotgallnematoder	Very broad host range
Globodera rostochiensis, Globodera pallida		Potato cyst nematodes	Potetcystenematoder	*Solanum tuberosum*, *S. lycopersicum*, *S. meongena*
Bursaphelenchus xylophilus	*Bursaphelenchus lignicolus*	Pinewood nematode	Furuvednematode	Conifer wood
Protozoa				
Plasmodiophora brassicae		Clubroot	Klumprot	*Brassica* species
Fungi				
Fusarium spp.			Sigdmuggsopper, Fusariose	Various *Curcurbita* and *Musa* species, *Gossypium*, *Ipomoea batata*, legume crops, *Nicotiana tabacum*, *S. lycopersicum*,

Organism (current binomial name)	Previous binomial names, synonyms	English common name/name of disease	Norwegian common name/ name of disease	Range of host plants and material
Olpidium brassicae	*Asterocystis radices* *Chytridium brassicae* *Olpidiaster radices* *Pleotrachelus brassicae*	Olpidium seedling blight		*Arachis hypogea*, *Beta vulgaris*, various *Brassica oleracea* species, *Capsicum annum*, *Cucumis sativus*, *Daucus carota*, *Lactuca sativus*, *Nicotiana tabacum*
Penicillium expansum		Blue mould	Eplepenselmugg	*Malus domestica* (post harvest)
Synchytrium endobioticum (Schilbersky) Percival		Potato wart disease	Potetkreft	Various Solanaceae species, *e.g.*, *S. tuberosum*, *S. lycopersicum*
Sclerotinia minor		Sclerotinia blight, Sclerotinia disease of lettuce		Very broad host range (>94 plant species)

Organism (current binomial name)	Previous binomial names, synonyms	English common name/name of disease	Norwegian common name/ name of disease	Range of host plants and material
Sclerotinia sclerotiorum		Cottony soft rot, White mold, Collar rot, Sclerotinia blossom blight, Sclerotinia canker, Sclerotinia disease, Sclerotinia drop, Sclerotinia head rot, Sclerotinia pod rot, Sclerotinia soft rot, Sclerotinia stalk rot, Sclerotinia stem rot, Sclerotinia twig blight, Sclerotinia wilt, Watery pod rot, White mould, white rot	Storknollet råtesopp	Very broad host range (>400 plant species)
Tilletia indica Mitra		Karnal bunt Partial bunt	Sotsopp (har ikke norsk navn)	Seeds of *Triticum aestivum*
Fungal-like organisms				
Phytophthora spp.				Very broad host range

Organism (current binomial name)	Previous binomial names, synonyms	English common name/name of disease	Norwegian common name/ name of disease	Range of host plants and material
Phytophthora fragariae Hickman	*Phytophthora fragariae* var. *fragariae* Hickman	Strawberry red stele root rot, Raspberry Root rot, Red core disease of strawberry, Red core of strawberry, Red stele disease of strawberry, Lanarkshire disease	Rød marg	*Fragaria* x *ananassa, Rubus idaeus*
Phytophthora ramorum		Ramorum dieback, sudden oak death (SOD)	Ramorum greinvisning	Very broad host range amongst deciduous trees and shrubs
Phytophthora rubi Wilcox & Duncan	*P. fragariae* var. *rubi* Wilcox & Duncan	Root rot of red raspberry	Rød rotråte, Bringebærrotråte	*Rubus idaeus, R. loganobaccus*
Bacteria				
Clavibacter michiganensis subsp. *michiganensis*	*Aplanobacter michiganense* *Bacterium michiganense* *Corynebacterium michiganense* *Mycobacterium flavum subsp. michiganense* *Phytomonas michiganensis* *Pseudomonas michiganensis*	Bacterial wilt and canker of tomato		Various Solanaceae species, *e.g.*, *Solanum lycopersicum*, *S. nigrum, Capsicum annum*

Organism (current binomial name)	**Previous binomial names, synonyms**	**English common name/name of disease**	**Norwegian common name/ name of disease**	**Range of host plants and material**
Clavibacter michiganensis subsp. *sepedonicus*	*Clavibacter sepedonicus* *Corynebacterium michiganense subsp. sepedonicum* *Corynebacterium sepedonicum*	Bacterial ring rot of potato, Ring rot of potato	Lys ringråte	Various Solanaceae species, in particular, *Solanum tuberosum*
Dickeya spp.				Broad host range
Ralstonia solanacearum (Smith) Yabuuchi et al.	*Burkholderia solanacearum* *Bacillus solanacearum* *Pseudomonas solanacearum* *Pseudomonas batatae* *Pseudomonas ricini*	Bacterial wilt of potato	Mørk ringråte	Very broad host range, *e.g.*, *Arachis hypogea*, *Musa*, *Nicotiana tabacum*, *Solanum lycopersicum*, *S. melongena*, *S. tuberosum*, *Tectona grandis*, *Zingiber officinale*
Streptomyces scabies	*Streptomyces scabiei* *Oospora scabies* *Actinomyces scabies*	Common scab of potato	Flatskurv på potet	*Beta vulgaris*, *Brassica napa*, *Dauca carota*, *Pastinaca sativa*, *Raphanus sativus*, *Solanum tuberosum*
Viruses				
Tobamoviruses (e.g Tobacco mosaic virus, Tomato mosaic virus, Pepper mild mottle virus, tomato brown rugose fruit virus, Sunn-hemp mosaic virus)	N/A	N/A	N/A	Broad host range, *e.g.*, *Beta* vulgaris, *Capsicum annum, Cucumis sativus*, *Lactuca sativa*, *Nicotiana* tabacum, *S. lycopersicum*

Organism (current binomial name)	Previous binomial names, synonyms	English common name/name of disease	Norwegian common name/ name of disease	Range of host plants and material
Plant material and seeds				
Avena fatua L.		Wild oats	Floghavre	
Reynoutria japonica Houtt.	*Fallopia japonica* (Houtt.) *Polygonum cuspidatum* (Sieb. & Zucc.)	Japanese knotweed	Parkslirekne	
Echinochloa crus-galli (L.) Beauv.	*Panicum crus-galli* L.	Cockspur grass, Barnyard grass	Hønsehirse	
Heracleum mantegazzianum Sommier & Levier	*H. giganteum, H. grossheimii*	Hogweed, Giant hogweed, Cart-wheel flower, Giant cow-parsnip	Kjempebjørnekjeks	

The description of process technologies and parameters is based on handbooks related to anaerobic digestion and composting (Döhler et al., 2013; Insam et al., 2010; Polprasert, 2007; Stofella and Kahn, 2001; van der Wurff et al., 2016; Waldron, 2007). Legal standards and directives were extracted from the background information provided by the Norwegian Food Safety Authority and the Norwegian Environmental Agency.

Table 2. Search terms and search terms combinations included in the literature survey.

Search terms	**Searches**
#1 "Heat treatment" #2 "Thermal inactivation" #3 Organisms: Current binomials, synonyms, previous Latin binomials and common English names (see Appendix II) #3 "Thermal inactivation" #4 Composting #5 "Anaerobic digestion"	Search 1: #1+ #2 +#3 Search 2: #4 + #3 Search 3: #5 + #3

Table 3. General and specific criteria for inclusion and exclusion of literature with respect to the terms of references (ToR)

Criteria	Inclusion criteria	Exclusion criteria
General	Original peer-reviewed published articles and reports with original data that met the following criteria were considered for inclusion: 1) Included ≥ 1 of the search terms 2) Key concept addressed ("Composting", "Anaerobic digestion", "Anaerobic fermentation" and "Thermal inactivation") 3) Included the identified organisms	1) Publications that did not address key concepts are excluded 2) Publications that were not original peer-reviewed research articles or reports with original data 3) Publications that did not address the desired genus and species, respectively 4) Publications that did not contain sufficient evidence[1] or only single papers 5) Publications dealing only with the disease-suppressive use of compost and digestates 6) Publications in a language other than English, German or Scandinavian languages
Specific criteria for the individual terms of reference (ToR)		

[1] Number of replicates and/or relevant scientific design with respect to treatment, sampling site, sampling number, replicates and repetitions as well as display of supporting parameters.

Criteria	Inclusion criteria	Exclusion criteria
1.a	Assessed for composting in windrows (> 2.5m) or mattresses where the temperature of the windrow is at least 55 °C for four weeks and the windrow is turned at least three times during this period. Also assess a variation of this whereby sanitation is divided into four periods with a temperature of at least 55 °C for at least one week, but where there can be intervals between each of these periods during which temperature is not measured. The material must be turned between each of these four periods.	Assessed for temperatures below 55° C or for periods shorter than 4 weeks
1.b	Assessed for the effect of heat exposure (70 °C) for 1 hr on interactions or associations with inactivation, inhibition of germination, reproductive failure, reproductive reduction, death or viability. Mesophilic AD data were evaluated in the presence and absence of heat exposure (70 °C), 1 hr to specifically examine the effect of the heat treatment.	Exposure to heat at < 70 °C or at higher temperatures (e.g. 80 °C, 90 °C, 110 °C), for other periods of time than 1 hr
2	Assessed for heat exposure and interactions or its association with inactivation, inhibition, viable but non-culturable stage (VBNC) and persistent cells with respect to *Escherichia coli*, *Salmonella* Senftenberg (775W H2Sneg), eggs/oocysts of *Ascaris suum*.	
3	Assessed for dispersal/spread/transmission by leakage, wind, aerosols, animals (insects, rodents, birds), management, cross contamination from biogas and composting facilities during pre- and post-process storage, pre- and post-process treatment, composting technology, post-process handling	

Criteria	Inclusion criteria	Exclusion criteria
4	Identified harmful alien organisms that may result in highly negative consequences if they are spread from composting and biogas facilities. Such organisms may be those: i) not commonly found (or are widespread) in Norway but able to spread if introduced; ii) causing significant damage to crop plants under Norwegian conditions iii) being able to survive and spread from composting facilities	Exclusion of organisms: those organisms that are already widespread in Norway and innocuous or that do not cause significant damage, organisms that would pose serious threats but are highly unlikely to occur and organisms that are not assumed to be able to survive if they spread from composting facilities.

In total, 3882 documents were retrieved through systematic Web of Science literature searches. Of these, 3024 documents were excluded on the basis of the criteria for exclusion given in Table 3; most exclusions were made based on exclusion criteria 1-6. Some organisms were excluded in the final results due to the dearth of literature references (e.g. *Tilletia* spp.), whereas others were excluded because they were deemed easy to inactivate by using the treatment conditions specified in ToR 1 (e.g. *Penicillium expansum* and wild oats; *Avena fatua*).

Assessment

1 Introduction

Organic wastes may be decomposed anaerobically (in the strict absence of oxygen) or aerobically (in the presence of oxygen). Due to the difference in atmospheric conditions, the processes, their preconditions as well as interim and final products are fundamentally different. Both processes need to be adjusted with respect to the composition of the feedstock. Fig. 1 displays processes, pathways and products for reflux of organic resources to plant production purposes. Four fundamental processing steps may be considered, namely

- Incineration
- Pyrolysis (resulting in biochar)
- Aerobic fermentation (composting)
- Anaerobic fermentation (digestion) (Alsanius et al., 2020).

In this evaluation, no attention is given to incineration and pyrolysis. The evaluation is limited to plant pathogenic considerations and intrusion as well as inhibition of alien organisms. It does not consider plant nutrient related aspects unless they are of importance for the evaluation specified above. Table 4 informs on waste quantities handled in compost and biogas facilities in Norway.

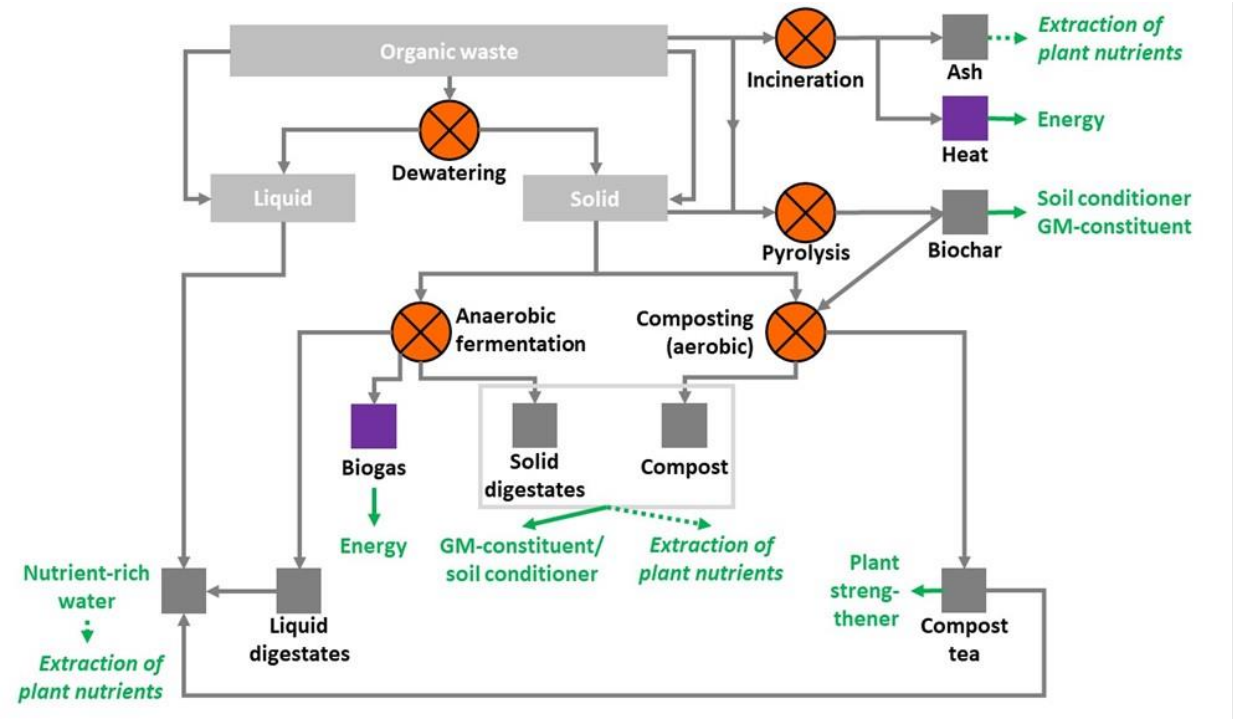

Figure 1. Processes, pathways and products recapturing resources from organic waste (Alsanius et al., 2020) , reproduced with permission of Burleigh Dodds Science Publishing). Orange circles denote processes whereas light grey boxes represent feedstock and its fractions. The dark grey boxes indicate solid or liquid (e.g., liquid digestates, compost tea) final products that may be used as growing medium (GM) constituents, as soil conditioners or as complex fertilizers. Biochar may also be amended as a feedstock constituent to composting. Purple boxes display final products that may be used as energy sources. Grey arrows show process flows. Green arrows denote pathways to final products, where the need for additional refinement and processing steps are marked by dashed lines. (Illustration: B. Alsanius). (Published in Wiskerke, J. (ed.), Achieving sustainable urban agriculture, Burleigh Dodds Science Publishing, 2020 – ISBN: 978 1 78676 316 7).

Table 4. Waste quantities (in kT) exposed to biological treatment (composting, anaerobic digestion) in Norwegian composting and biogas facilities during 2017 to 2020 (SSB, 2021)

	Waste quantities handled in							
	Composting facilities				Biogas facilities			
Year	2017	2018	2019	2020	2017	2018	2019	2020
Household kitchen waste	70	51	37	48	158	62	145	149
Food waste from catering and restaurants	0	4	11	9	0	69	39	37
Edible agricultural wastes	0	5	4	4	0	6	0	1
Plant based wastes from food industry	0	18	14	0	0	29	4	0
Animal by-products	0	0	0	16	0	6	22	1
Green wastes (park and garden waste)	68	76	73	115	14	0	0	0
Manure	7	7	6	9	63	64	74	76

1.1 Brief process description

1.1.1 Anaerobic digestion

Anaerobic digestion (AD) is a four-step approach, consisting of hydrolysis, acidogenesis, acetogenesis as well as methanogensis, facilitated by different groups of microorganisms. This process can take place under different temperature regimes, *i.e.*, under mesophilic or thermophilic conditions, respectively. Organic matter can be fed into the process in batches or continuously, in smaller or larger vessels or moving lines. For an optimal process, external factor control, such as temperature, pH and the carbon to nitrogen ratio (C/N ratio) of the feedstock, is essential. The process time (residence time) depends on system configurations, feedstock composition and moisture content (wet, dry). Apart from nutrient-rich liquid and solid digestates, AD generates methane (biogas). To assure hygienic properties of the end product, the food waste needs to be heat-treated (pasteurized). Decisive parameters and pathways in AD are presented in fig. 2. More detailed information on AD can be extracted from Insam et al. (2010).

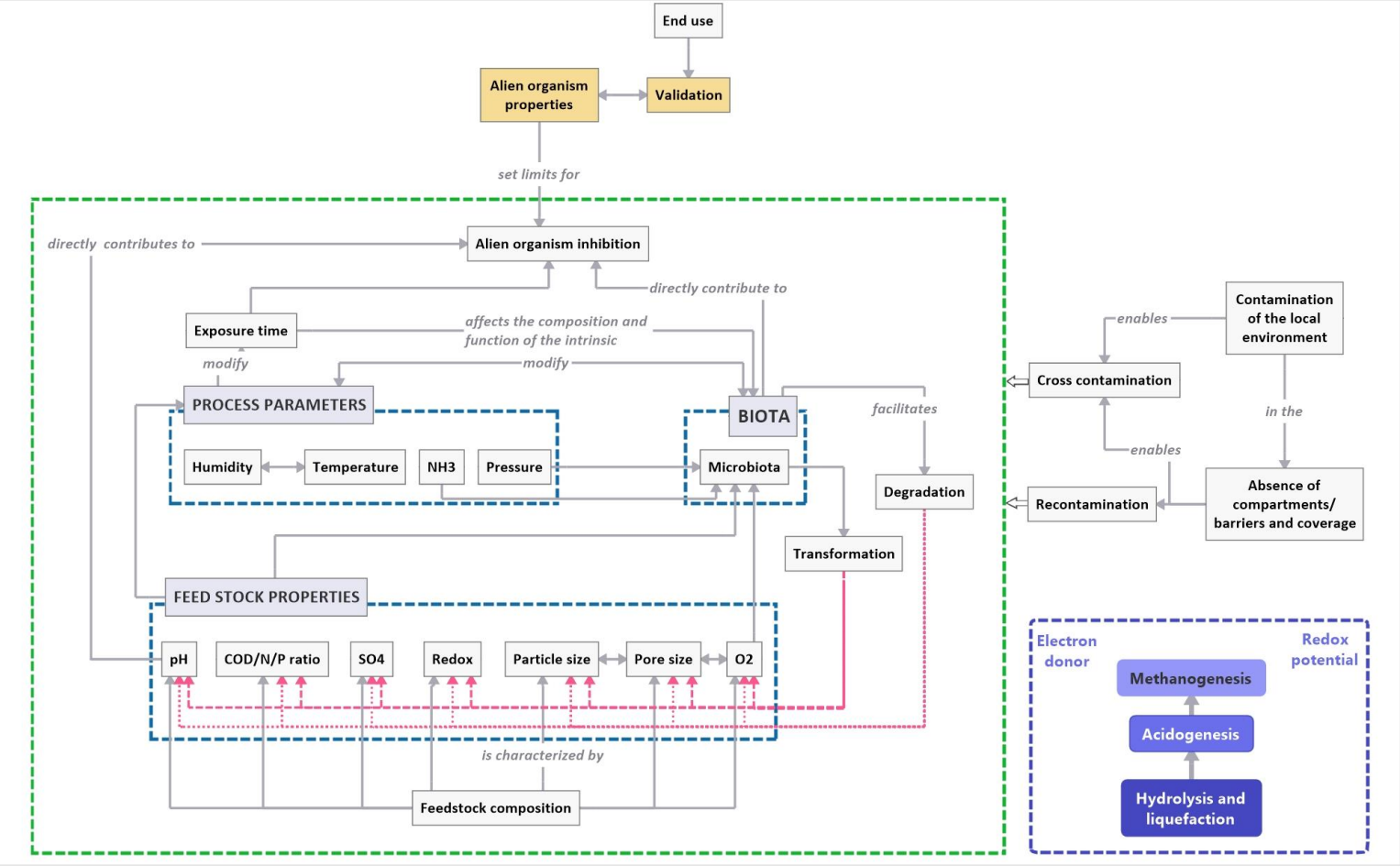

Figure 2. Anaerobic digestion concept map. Pathways of importance for interactivities between abiotic and biotic factors, intrusion and inhibition of alien organisms are considered. (Illustration: B. Alsanius)

Various process techniques optimized for biogas production have been developed using AD. Wet, but not dry digestion systems are used in Norway. Processes for wet digestion are briefly described in Table 5. Pre- and post-process hygienization may be integrated.

Table 5. Description of techniques used for wet anaerobic digestion. (Process parameters: Temperature range: M indicates if the maximum temperature does not exceed 35 °C (mesophilic) whereas T denotes temperature regime reaching 55 °C (thermophilic). The predominant mode is indicated in bold font. Not all of the displayed techniques are used in Norway.

Process design	Short process description	Temperature
Horizontal plug flow system	Mostly horizontally placed fermenters made of stainless steel or reinforced concrete (ferroconcrete). A centrally placed agitator enables mixing. Fermenter allows feedstocks with high dry matter content. Continuous feed stock incorporation.	M, **T**
Vertical fermenter system	Stirred tank fermenter made of stainless steel or reinforced concrete. Centrally placed agitator enables mixing. Feedstock with medium dry matter content can be used. System allows large volumes, however, process control and mixing may be difficult in large volume systems. Fixed or floating dome solutions. Continuous feed stock incorporation.	M, T

1.1.2 Composting

Aerobic degradation of organic matter is also called composting. This process depends on biological, chemical and physical factors. The process is facilitated by a succession of different trophic groups of microorganisms; their activities lead to temperature increase. Four decisive phases can be discriminated

(i) Latent phase
(ii) Mesophilic phase (facilitated by bacteria)
(iii) Thermophilic phase (mediated by bacteria, esp. actinomycetes (bacteria) and fungi)
(iv) Second mesophilic phase (cooling phase)
(v) Ambient phase (curing and maturing phase).

The latter two phases belong to the so-called curing phase and are facilitated by 2nd and 3rd degree consumers.
Composting may take place in open or closed (insulated), stationary or mobile containers or vessels, and may be performed in small, medium and large size facilities. It can be conducted under open air conditions, under roofed surfaces or indoors (*e.g.*, stack composting, windrows, drums). Choice of site and insulation of vessels is important for temperature management to ensure that the evolved temperature is spread homogeneously across the entire feedstock. For food wastes, insulation is mandatory to avoid the proliferation of vermin. As for AD, feedstock size is an important feature; variations in feedstock composition have a stronger impact on small units as opposed to larger ones. The nutrient-rich end products from the composting process may be liquid (compost tea) or solid (compost) (Figs 1, 3). More detailed information on the composting process is available in Insam et al. (2010). Various techniques are used for composting (Table 6).

Aerobic degradation of organic material assisted by various detritivorous earthworms (*e.g.*, *Eisenia fetida*, *Eudrilus eugeniae*) is called vermicomposting. The end product can be separated into three fractions: worm castings, vermicompost and vermicompost tea. Vermicompost can be produced in small (*e.g.,* under the kitchen sink), medium or large units, in- or outdoors. Vermicomposts are commonly managed through continuous feeding. Adequate moisture management of the vermicompost feedstock is necessary

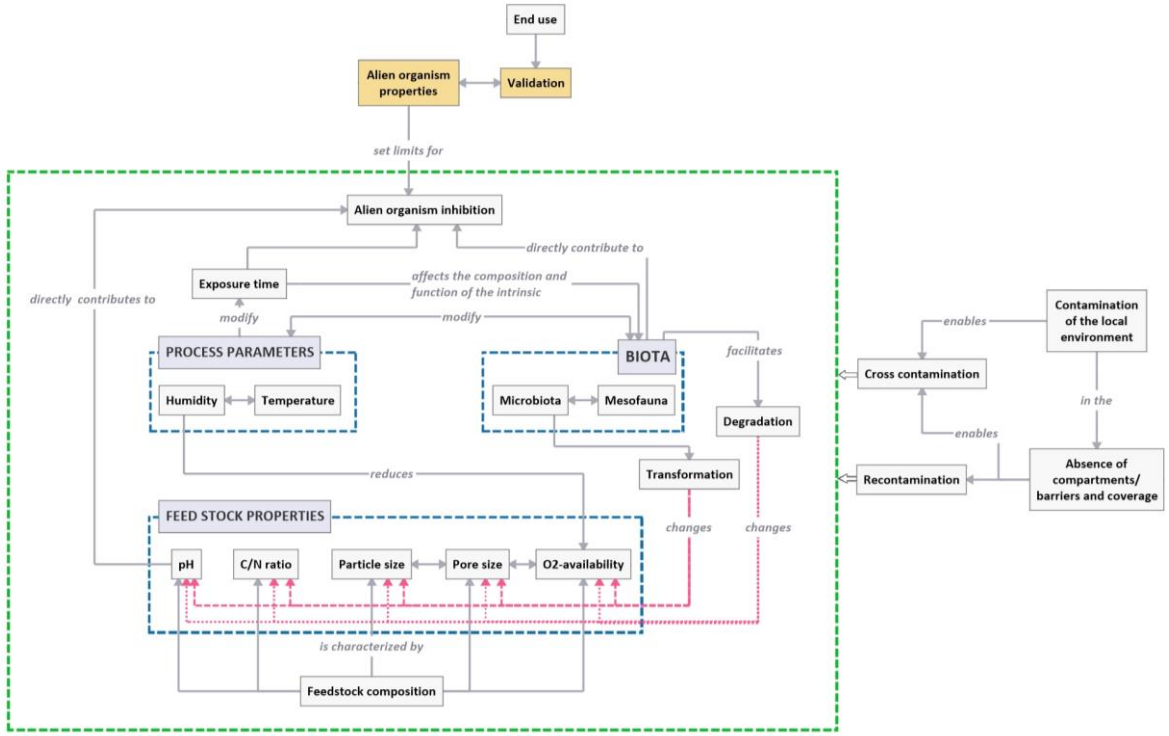

Figure 3. Compost concept map. Pathways of importance for interactivities between abiotic and biotic factors, intrusion and inhibition of alien organisms are considered. *(Illustration: B. Alsanius)*

Table 6. Technique and system parameters for general composting of solid organic wastes.

Process design	Short process description
Open systems	
Aerated pile composting	On site composting of solid wastes (such park and green waste) with active aeration; aeration through positive (using fans and ducts) or negative pressure (suction); food and kitchen as well as wastes from animal industry (e.g., slaughterhouse) should be avoided; aeration twice a day for 15 min; process length: 4 –5 weeks.
Passively aerated pile	On site composting of solid wastes (such park and green waste) without active aeration; passive aeration process through wind, diffusion or thermal convection; outdoor or indoor application; periodical turning; food and kitchen as well as wastes from animal industry (e.g., slaughterhouse) should be avoided; variable process length: up to 4 years with turning once a year. *Example for large scale applications: mattress composting of park and green wastes.*
Open basket composting	Backyard composting of green/garden wastes in open passively aerated baskets; food and kitchen wastes should be avoided; turning interval: once a month to once a year; process length varies accordingly from 16-20 weeks and several years.
Static pile composting	Composting in open piles without turning.
Windrow composting	Actively (forced air) or passively aerated (through manual or mechanical turning) degradation process in which the organic wastes are piled in windrows. Varying turning intervals according to compost age (more intensive during the first 2-3 weeks daily or every second day; less intensive during following 6-8 weeks with turning each week or every second week). Also, processes without turning occur. Windrow height: 2-5 m depending on feedstock; Process length: 8-52 weeks.
Contained systems	
Aerated containers	Aerobic decomposition in a static pile with forced aeration in a fully enclosed system; varying container size, from very small (polyethylene bag) to worn-out lorry or ship container.

Process design	Short process description
Aerated agitated beds	Beds: decomposition in long narrow beds limited by concrete walls, sealed floor, but open top. Agitation is managed through top-steered turners. Feedstock loaded at one short end of the bed and de-loaded at the opposite side. Material moved horizontally along the bed over time. Process length: 1.5-4 weeks.
Aerated agitated containers	Automated system with forced aeration where the feedstock filled trays are moved through a tunnel with two temperature zones. Trays are agitated while moving from zone to the next.
Rapid digestion composting	Horizontal automated system supporting a rapid turn-over of organic matter by heat and addition of enzymes. Small, individual compost units, filled batchwise; Process length: 1 day or shorter.
Rotating drum composting	Horizontally slowly or intermittently rotating drum. Feedstock loaded at one end of the drum and compost removed at the opposite end. Rotation enables mixing, agitation and moving of the feedstock through the drum. Large drums may be divided in several compartments. Process length: 0.5-1 week.
Tower composting	Top-loaded system using silos using forced aeration. Material moves through the tower as composted matter is removed from the bottom of the tower. Process length: 1.5-4 weeks.
Vermi-compost	Decomposition of green waste, food and kitchen wastes as well paper in containers or windrows engaging worms such as *Eisenia fetida* and *Echytraeus buchholzi* . Process length: 12-26 weeks.

1.2 Process parameters

This section deals with the impact of process parameters on microorganisms during AD and composting. The vast majority of literature treats undesired human pathogens in this regard, whereas the fate of plant pathogens and seeds has received much less attention. Therefore, information on the interaction of process parameters on human pathogens is given in some cases.

1.2.1 Temperature

Both composting and anaerobic digestion are based on wet heat. The obtained process temperature during aerobic and anaerobic fermentation is important for the state of the degraded material as well as for its hygienic properties. Fermentation under mesophilic conditions does not exceed 45 °C, whereas fermentation under thermophilic conditions reaches 65-70 °C during composting. Maximum temperature during AD is adjusted to optimized biogas extraction. Optimum temperature varies between the different process steps (hydrolysis/acidogenesis: 55-65 °C; mesophilic acetogenesis/methanogenesis: 32-42 °C, thermophilic acetogenesis/methanogenesis: 50-57 °C).

Various publications emphasize the dominant impact of temperature on the composting process itself and the presence of viable pathogenic structures (Lung et al., 2001. ; Pereira-Neto et al., 1986). Whereas vegetative cells, especially exponentially growing cells, may be killed at temperature levels soaring during the mesophilic and thermophilic phases, bacterial spores and other survival structures are more heat-resistant. Heat resistance to sublethal temperature levels can be induced in growing vegetative cells as a consequence of slow heating, but also as a cross reaction to other suboptimal environmental conditions (Sing et al., 2010; Smelt and Brul, 2014), *e.g.*, low pH, nutrient and osmotic stress, as well as the presence of some organic acids (Franz et al., 2005; Smelt and Brul, 2014). This underlines that the course of the heating process, but also the heat distribution within the pile (Huet et al., 2012) as well as the equilibrium between microbial heat generation and heat losses (Cekmeceliglu et al., 2005; Déportes et al., 1998) during the composting process are essential for the outcome. Apart from the maximum temperature levels themselves, exposure time as well as chemical and physical feedstock properties (such as humidity, pH) are crucial for microbial inactivation and death. For example, heat and moisture content were essential for reduction in viable count of *Salmonella* ssp. and *E. coli* during composting of chicken manure and feed under laboratory conditions (highest efficacy at temperatures >60 °C, moisture content of 100%; Gradel et al. (2003)). Furthermore, it is worthwhile to mention, that high temperatures (>55 °C) during composting will promote inactivation of unwanted organisms, but on the other hand slows down organic matter degradation (Eklind et al., 2007).

Interestingly, greatly lowered inactivation temperatures were reported in a series of AD incubation experiments including several major plant pathogens (Seigner et al., 2010). In many cases, inactivation already occurred at comparably low temperatures (38-39 °C), given the length of exposure was sufficiently long. The duration until inactivation of the tested model organisms could be as short as 8 h (*Sclerotinia sclerotorium*) and up to 100 d (*Clavibacter michiganensis* subsp. *sepedonicus*); whereas other organisms still showed very high survival of survival spores (*Synchytrium endobioticum*) after 137 d. Apart from exposure time, other process parameters of anaerobic digestion also are important. Pathogens cope more successfully with a high temperature in complex organic matter and if the substrate is not sufficiently moist.
Critical temperatures for inactivation of unwanted organisms are summarized in Table 7.

Table 7. Summary of critical levels of temperature and humidity, matrices used and duration of exposure for inactivation of selected model organisms, as based on the literature search

	Organism	***Properties***				***References***
		Temp	***Humidity***	***Material/ process***	***Exposure time***	
Insects	*Epitrix sp.*[2]	*<50 °C*				*Refs in VKM et al. (2018)*
Nematodes	*Globodera pallida*	*90 °C*	*Dry*	*Cysts*	*1 min*	*Stone and Wesley (1975)*
	G. pallida	*80 °C*	*Wet*	*Cysts*	*1 min*	*Stone and Wesley (1975)*
	G. pallida	*50 °C*	*Wet*	*Cysts*	*4 min*	*Stone and Wesley (1975)*
	Globodera rostochiensis	*58-59 °C*	*Water*	*Juveniles*	*30 min*	*Evans (1991)*
	G. rostochiensis	*40 °C*	*Wet*	*Cysts in water*	*7 days*	*LaMondia and Brodie (1990)*
	G. rostochiensis	*50 °C*	*Wet*	*Cysts in water*	*5 min*	*LaMondia and Brodie (1990)*
	G.rostochiensis	*55 °C*	*Dry soil*	*Cysts in dry soil*	*47 h*	*LaMondia and Brodie (1990)*
	G. rostochiensis	*40-50 °C*	*Wet*	*Compost*	*5-7 days*	*Bøen et al. (2006)*

[2] Epitrix species are short-lived in water, soil, waste and plant debris.

	Organism	***Properties***				***References***
	G. rostochiensis	*65 °C*	*Wet*	*Sludge*	*30 min*	*Holgado et al. (2013)*
	G. rostochiensis	*65 °C*	*Wet*	*Sludge*	*60 min*	*Holgado et al. (2013)*
	Meloidogyne incognita	*73 °C* *57 °C*	*Humid*	*Compost*	*4 days* *19 days*	*Herrmann et al. (1994)* *Witchuk et al. (2011)*
	Meloidogyne chitwoodi	*58 °C*	*Humid*	*Compost*	*42 hrs*	*Witchuk et al. (2011)*
	Melodiogyne fallax	*73 °C*	*Humid*	*Compost*	*4 days*	*Expert judgement*
	Bursaphelenchus xylophilus	*56 °C* *65 °C*	*Variable*	*Pine wood*	*30 min* *>30 min*	*ISPM 15* *Qi et al. (2005)*

	Organism	*Properties*				*References*
Protozoa	*Plasmodiophora brassicae*	*64-70 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested cabbage roots in nylon bag, placed in garden refuse compost*	*4 months*[3] *(64-70 °C maintained for 21 days)*	*Bollen et al. (1989) (1 of 54 survived)*
	P. brassicae	*47-65 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested cabbage roots in nylon bag, placed in garden refuse compost*	*8 months*[3] *(47-65 °C maintained for 3-4 weeks)*	*Bollen et al. (1989)*
Fungi	*Synchytrium endobioticum (Potato wart disease)*	*60 °C*		*Compost*	*8 hours*	*Glynne (1926)*

[3] Lower cut-off of duration of time not known, since this was the only period tested.

	Organism	***Properties***				***References***
	S. endobioticum (Potato wart disease)	*65 °C*	*Moist*	*Wart spores suspended in paste, placed in compost*	*Not possible to kill (> 12 days)*[4]	*Steinmöller et al. (2012); Steinmöller et al. (2007)*
	S. endobioticum (Potato wart disease)	*70 °C*	*100% RH*	*Water bath*	*Not possible to kill (>90 min)*[4]	*Steinmöller et al. (2012); Steinmöller et al. (2007)*
	Olpidium brassicae[5]	*56-67 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested lettuce root clods in compost of garden and greenhouse refuse*	*Composting for 5 months*[3] *(56-67 °C maintained for 3-4 weeks)*	*Bollen et al. (1989)*

[4] The time-temperature combinations were not sufficient for total eradication; survival is indicated by the sign "> "(greater than).

[5] if species info is a limitation, look for the genus in general.

	Organism	Properties				References
	Fusarium lilii	*58-70 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested lily bulbs in compost of garden and greenhouse refuse*	*Composting for 5 months[3]* *(58-70 °C maintained for 3-4 weeks)*	*Bollen et al. (1989)*
	Fusarium oxysporum f.sp. melonis	*56-67 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested melon roots and stem bases in compost of garden and greenhouse refuse*	*Composting for 5 months[3]* *(56-67 °C maintained for 3-4 weeks)*	*Bollen et al. (1989)*
	Fusarium oxysporum f.sp. cucurbitae	*53-65 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested zucchini roots and stems in nylon bag, placed in garden refuse compost*	*Composting for 7 months[3]* *(53-65 °C maintained for 3-4 weeks)*	*Bollen et al. (1989)*

	Organism	Properties				References
	Fusarium oxysporum f.sp. melogenae	*53-65 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested eggplant root clods in nylon bag, placed in garden refuse compost*	*Composting for 7 months[3]* *(53-65 °C maintained for 3-4 weeks)*	*Bollen et al. (1989)*
	Fusarium oxysporum f.sp. callistephi	*47-65 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested chinese asters in nylon bag, placed in garden refuse compost*	*Composting for 8 months[3]* *(47-65 °C maintained for 3-4 weeks)*	*Bollen et al. (1989)*
	Fusarium oxysporum f.sp. lycopersici	*65 °C*	*40-58% DM in compost*	*Wheat kernels placed in compost*	*More than 21 days[4]*	*Christensen et al. (2001)*
	Fusarium oxysporum radicis-lycopersici	*70 °C*	*-*	*Fungal culture in PDA*	*1 hour*	*Henry et al. (2013)*

	Organism	***Properties***				***References***
	Fusarium culmorum	*70 °C*	*-*	*Fungal culture in PDA*	*1 hour*	*Christensen et al. (2001)*
	Sclerotium cepivorum	*35-37 °C*	*Water added. DM was 39% in the bioreactor*	*Detached sclerotia of onions mixed with sand in a nylon bag, inserted in feedstock of vegetable, fruit and garden waste, subjected to MAD*	*More than 6 weeks[4]*	*Termorshuizen et al. (2003)*

	Organism	Properties				References
	S. cepivorum	*64-70 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested onion bulbs in nylon bag, placed in garden refuse compost*	*Composting for 4 months[3]* *(64-70 °C maintained for 21 days)*	*Bollen et al. (1989)*
	Sclerotinia sclerotiorum	*64-70 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested lettuce stem bases in nylon bag, placed in garden refuse compost*	*Composting for 4 months[3]* *(64-70 °C maintained for 21 days)*	*Bollen et al. (1989)*
Fungal-like organisms (Oomycetes)	*Phytophthora cryptogea*	*64-70 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested Chinese aster root clods in nylon bag, placed in garden refuse compost*	*Composting for 4 months[3]* *(64-70 °C maintained for 21 days)*	*Bollen et al. (1989)*

	Organism	***Properties***				***References***
	Phytophthora infestans	*47-65 °C*	*60-80 % RH at beginning; 50% at the end*	*Infested potato tubers in nylon bag, placed in garden refuse compost*	*Composting for 8 months[3]* *(47-65 °C maintained for 3-4 weeks)*	*Bollen et al. (1989)*
	Phytophthora nicotianae	*45 °C*	*36.8 ± 3% moisture*	*Green waste compost in laboratory flasks*	*7 days*	*Noble et al. (2011b)*
	Phytophthora cinnamomi	*40 - 60°C*	*85% moisture*	*Infected plant material in ground hardwood bark compost*	*10-12 weeks[3]*	*Hoitink et al. (1976)*

	Organism	**Properties**				**References**
	P. cinnamomi	*> 60 °C*	*40 % moisture*	*Chlamydospores in fresh, ground green waste (compost from tree clippings, turfgrass)*	*1 week*[3]	*Downer et al. (2008)*
	Phytophthora ramorum	*55 °C*	*No data given*	*Artificially infected oak stems or laurel leaves*	*2 weeks*	*Swain et al. (2006)*
Bacteria	*Ralstonia solanacearum*	*>45 °C (constant)* *60 °C (constant)*	*Wet; not defined in the abstract*	*Soil*	*2 days* *2 h*	*Kongkiattikajorn and Thepa (2007)*

	Organism	Properties				References
	R. solanacearum	*45 °C (cyclic)* *50 °C (cyclic)* *Cycle length: 2 h*	*Wet; not defined in the abstract*	*Soil*	*3 days* *2 days*	*Kongkiattikajorn and Thepa (2007)*
	R. solanacearum	*45 °C (cyclic)* *50 °C (constant)*	*Dry; not defined in the abstract*	*Soil*	*2 days* *1 days*	*Kongkiattikajorn and Thepa (2007).*
	Clavibacter michiganensis subsp. michiganensis	*35 °C ± 2 °C*	*Approx. 5 % DM*	*Infested tomato stems mixed into domestic sewage sludge/anaerobic digestor*	*7 days*	*Turner et al. (1983)*

	Organism	Properties				References
	C. m. subsp. michiganensis	*40-65 °C during thermophilic phase (up to 80 days); thereafter approx. 35-40 °C*		*Compost 50 to 60% humidity during the thermophilic period and at 40– 50% thereafter*	*15-20 days (during the thermophilic phase)*	*Yogev et al. (2009)*
	C. m. subsp. sepedonicus	*>55 °C*		*Ready-made mould compost. They survived!*	*>21 days*	*Steinmöller et al. (2013)*
	C. m. subsp. sepedonicus			*Composting of naturally-infested tomato stems*	*130 days*	*Raviv et al. (2010)*
Viruses	*Tobacco Mosaic Virus (TMV)*	*70 °C*			*2-3 weeks*	*Christensen et al. (2001)*

	Organism	***Properties***				***References***
	TMV	*78 °C*	*Plant tissue*	*Compost*	*57 days*	*Ryckeboer (2001)*
	TMV	*31 °C*	*Plant tissue*	*Compost*	*26 weeks*	*Ryckeboer (2001)*
	TMV	*Thermophilic anaerobic digestion followed by composting at 58 °C*	*Plant tissue*	*Compost*	*3 + 2 weeks*	*Ryckeboer et al. (2002)*
Plants	*Reynoutria japonica*[6]	*55 °C*	*Moist*	*Composting of plant parts*	*3 days*	*Day et al. (2009)*

[6] Propagules used: rhizome parts, leaves and stem fragments. Rhizome parts are probably not destroyed during MAD, since they are very robust in contrast to above-ground plant parts. Therefore, composting or AD of this plant is not recommended for garden owners in some countries.

	Organism	Properties				References
	Echinochloa crus-galli	*49 °C*		*Seeds buried in compost*	*3 days*	*Wiese et al. (1998)*
	E. crus-galli	*37 °C*	*Moist*	*Anaerobic digestion*	*30 days*	*Westerman et al. (2012)*
	E. crus-galli	*42 °C*	*6.27% DM*	*Anaerobic digestion*	*24 h/32h (time depending on seed batch)*	*Zhou et al. (2020)*
	E. crus-galli	*45-50 °C (in deep layer); 30 °C (in subsurface layer)*		*Anaerobic digestion*	*within 1 month (36% of seeds survived)*	*Šarapatka et al. (1993)*
	Heracleum mantegazzianum	*37 °C*		*Anaerobic digestion*	*40 days*	*Van Meerbeek et al. (2015)*
	H. mantegazzianum	*42 °C*	*100% RH*	*Water bath*	*2 days*	*Tanke et al. (2019)*
		35 °C	*100% RH*	*Water bath*	*8 days*	*Tanke et al. (2019)*

1.2.2 Moisture/humidity

For an optimal aerobic degradation process, 50-70% moisture is suggested during the thermophilic phase, and at moisture levels below 20% degradation is inhibited. Feedstock constituents with higher moisture content need to be supplemented with bulking material to obtain optimum conditions. During composting, free water is generated but also lost through heat emission, especially when forced aeration is employed.

Norwegian biogas facilities commonly apply wet digestion (Jens Måge, Avfall Norge, pers. communication), in which dry matter content may not exceed 15% (Döhler et al., 2013).

1.2.3 pH

The two principles for organic matter decomposition differ fundamentally in their pH management approach. As energy production is the main purpose of AD, the process is optimized also with respect to pH. Optimum pH conditions vary during the different phase with pH ranges pH 4.5 to 7 during hydrolysis and acidogenesis and 6.8-8.2 during acetogenesis and methanogenesis (Döhler et al., 2013).

In contrast to the meticulously managed process in anaerobic digestion, pH in compost feedstocks evolves as a consequence of microbial activity in combination with organic matter decomposition but is also a process driver. It is influenced by three acid-base systems. Ideally, the optimum pH in the compost feedstock ranges from pH 6.5-8.5. During the initial phase, the pH drops to slightly acidic levels (pH 5-6) which then is followed by a rise in pH. The pH of mature composts ranges between pH 7.5 and 8.5. The course of pH evolution is affected by the feedstock composition. The pH conditions have an impact on the microbial community composition structure (Wang et al., 2015), favoring fungi on behalf of bacteria during the acidic phase, while feedstock sanitation may occur during the alcalinic phase. The pH conditions (low pH) may also hamper temperature succession, as the transition from mesophilic to thermophilic conditions may be impaired (Sundberg et al., 2004). This needs to be taken into account when designing the feedstock mix (Bergersen et al., 2009; Zhang and Sun, 2015).

1.2.4 Atmospheric conditions

Given the aerobic nature of the composting process, access to oxygen is a fundamental prerequisite. Physical properties in the feedstock change during the composting process and thus, gas movement is affected. Anaerobic loci may occur. Inferior gas movement also leads to heterogenous heat distribution, resulting in spots that do not reach inactivation

temperature. This is counteracted through intermediate mixing or forced aeration. As expected, increased aeration of the feedstock during composting lead to increasing oxygen content but also to increased nitrogen emissions as demonstrated for composting of corn straw amended pig manure (Guo et al., 2012). Furthermore, aeration rate was shown to have a strong impact on compost stability.

Anaerobic digestion is dependent on the absence of oxygen. While hydrolysis and acidogenesis may take place at facultatively or obligate anaerobic conditions, strict obligate anaerobiosis is mandatory during acetogenesis and methanogenesis. Redox potentials for the first two (hydrolysis and acidogenesis) and the last two (acinetogenesis and methaongenesis) stages lie at +400 to –300 mV and <250 mV, respectively (Döhler et al., 2013).

1.2.5 Feedstock and C/N ratio

Feedstock constituents depicted in the terms of reference are (i) green waste (park and garden wastes incl. soil), (ii) wasted plants from garden centers, (iii) food waste and waste from the food and animal feed industry (including grain/seed husks and waste from enterprises which package and process potatoes and vegetables), (iv) manure, (v) bulking agents used in composting facilities and (vi) husks from contracted grain/seed cleaners for sowing. These groups are governed by different directives (Appendix III; Supplementary Table 1). Table 8 displays examples for feedstock constituents related to the different depicted classes and some decisive parameters.

Apart from the various matrixes that may be used as feedstock constituents, particle size as well as C/N:ratio is crucial. Both are closely linked to the degradation process. Particle size does not only govern the particles' specific surface but also pore size and the abundance of air-filled pores. As a consequence, it is also decisive for moisture content. While degrading, particle size changes and thus affects the other related parameters. For composting, a particle size of 3 mm to 50 mm and a free air space of 32-36% are optimum as mentioned by Stofella and Kahn (2001) and literature therein. For AD, particle sizes have been optimized with respect to methane yield. In the literature, conflicting results have been reported on the impact of feedstock particle size on methane formation (no impact: Zhang and Banks (2013); with impact: de la Rubia et al. (2011)). However, feedstock particle size influenced the AD process, causing process failure due to acidification and foam formation when fine particle size was used in dry and wet digesters, respectively (Zhang and Banks, 2013). Feedstock particle size is important for phytosanitary effects. *Clavibacter michiganensis* subsp. *sepedonicus* or *Ralstonia solanacearum* in intact potatoes survived AD at 38 °C during 100 d and 30 d (Seigner et al., 2010).

Feedstock composition (C/N: 17/1-34/1) have been shown to be crucial for the microbial community composition during composting (Neher et al., 2013). Also, other studies underline this fact. With regard to C/N ratio and the content of organic groups, *e.g.,* carbohydrates, have an impact on other process parameters, e.g., pH and heat evolution, but also on the fate of specific groups of microorganisms, including unwanted organisms. Using an extreme vertices mixture design to combine three constituents (food waste, cow manure, bulking material), (Cekmeceliglu et al., 2005) stated the most efficient reduction of *E. coli* and *Salmonella* spp. at a ratio of 0.45:0.40:0.15 (food waste/cow manure/bulking agent), but marginal changes with respect to fecal coliforms and fecal enterococci. In the context of chicken manure, a low C/N ratio (10:1) increased the occurrence (frequency?)of viable colonies of ESBL-producing *E. coli* during composting. especially at low moisture contents (20%, 40%) (Thomas et al., 2020).

Table 8. Common feedstock constituents for different groups of organic wastes (Table 8). Examples for different constituents common in Norway as well as ranges of decisive parameters are listed.

	Common constituents	Ranges of decisive parameters		
			C/N	pH
Park and garden waste	biodegradable garden waste and public park waste, such as grass clippings, leaves and shredded branches of deciduous and coni-ferous trees and shrubs, leaves; may contain stones and soil	Vegetable waste	10-12/1	NA
		Grass clipping	12-25/1	
		Leaves	30-80/1	
		Bark	100-130/1	
		Shredded wood and sawdust	100-500/1	
Wasted plants from garden centers	Removed infected and dead leaves or whole plants, spent growing medium	Peat	58	NA
		Coir, composted bark	78	

	Common constituents	Ranges of decisive parameters		
Food waste (kitchen waste)	Food of animal (fish and seafood, poultry and meat, egg, dairy), plant (fresh and processed fruits, vegetables, cereals, nuts) or microbial origin as well as fats and oils removed during food preparation, plate scraps/waste, spoiled food of animal, plant or microbial origin, incl. bones, skin, peels and rinds considered inedible, ground coffee; may contain packaging material, plastics, chipped glass and metal	Fish waste	6/1	
		Non-legume vegetable, *e.g.*, lettuce, onion, tomato, cabbage)	10-12/1	
		Potato tops	25/1	
		whole carrot	27/1	
		kitchen waste	19-29/1	3.84-4.6
		Coffee ground	30/1	
		Watermelon	30/1	
		Pineapple	46/1	
		Apricot	38/1	
		Lemon	34/1	
		Orange	54/1	

	Common constituents	Ranges of decisive parameters		
Waste from plant food processing industry	Potato packages, Potatoes incl. peel, spoiled or trimmed vegetables, spoiled or trimmed fruits, spent brewery grain, spent mushroom compost	Rice husk	87-91/1	
		Spent brewer grain	7.1-26.5	3.8-6.9
		Spent mushroom compost		6.8
		Coffee husk	18/1	
		Coffee pulp		9.7
			18-21/1	9
			37/1	
Waste from animal feed industry	Seed husks, grains	Alfalfa	30/1	
		Sunflower hulls	83/1	
Manure	Pig, cow, dairy or poultry manure	Pig manure	11/1	6.67
		Cow manure	21/1	8.53
		Poultry manure	25-30/1	

	Common constituents	Ranges of decisive parameters		
Bulking material	Needles of conifers, shredded wood, saw dust, spent pallets, cardboard, straw, hay, artificial bulking material	Wheat pellets	32	7.5
		Chopped hay	58	6.6
		Conifer needles	80/1	
		Chopped wheat straw	101/1	7.0
		Cardboard	131-223/1	7.2-7.7
		Sawdust	400/1	
		Shredded wood	100-500/1	
Husks and seeds from contracted grain and seed husk cleaners		Wheat brans	18/1-34/1	
		Cottonseed hulls	67/1	

1.2.6 Other parameters

Sanitation of degrading organic matter is predominantly governed by temperature levels and most literature highlights its importance with respect phytosanitary processes during AD and composting. However, the phytosanitary success is rather a consequence of synergism between different parameters, *e.g.*, temperature, atmospheric conditions, microbial antagonism, proteolytic activity, low pH and deleterious metabolites and toxic compounds than exclusively temperature (Seigner et al., 2010). Also, the level of disintegration and thus particle size of the contaminated feedstock is essential.

2 Assessment

2.1 Assessment of critical operating conditions

To obtain a high efficacy of sanitation for harmful alien organisms the operating conditions need to consider the kind of material to be treated, the species of pathogenic organism, their survival stages, the temperature, the humidity and the exposure time for inactivation of the pest.

2.1.1 Nematodes

The biotrophic plant parasitic nematodes are advanced as plant pathogens (Tronsmo et al., 2020). The process of parasitism involves several critical steps like host finding, root tissue penetration, selection of cells for the feeding site induction, and feeding site maintenance. Successful nematode parasitism therefore requires a high degree of fitness of the nematode to recognize and respond correctly to the signaling of the host plant. Temperatures and duration of exposure during composting would impair some, or all of these steps leading to reproductive failure.

Many nematode pests are easily killed, and most species of *Ditylenchus* spp., *Aphelenchoides* spp. and *Pratylenchus* sp. are inactivated at temperatures ranging between 44 -47 °C for a few minutes and up to four hours depending on the material treated (Bingefors et al., 1971). However, the nematodes selected as model organisms (Table 1) require special conditions for effective sanitation.

In the case of the pinewood nematode (PWN), *Bursaphelenchus xylophilus*, special conditions are laid down in ISPM 15 (IPPC). In the described heat treatment (HT), the temperature x time combination for sanitation should be 56 °C for 30 min. However, this treatment does not result in 100% killing of PWN. It is proposed that eradication of PWN would require temperatures of 65 °C for more than 30 min (Qi et al., 2005). This may be one reason for the interception of PWN in 1.2% of pallets by the Chinese inspection service in Ningbo. Interceptions of PWN were made also in pallets accompanied by a HT certificate (Gu, pers. comm).

Due to their status as quarantine pests and due to their importance in damaging potato, the potato cyst nematodes PCN (Fig. 4) *Globodera rostochiensis* and *G. pallida* has been in focus for a long time. Reports on the inactivation of the potato cyst nematodes (*G. rostochiensis* and *G. pallida)* vary considerably, probably caused by experimental and treatment conditions. In wet rycysts of *G. rostochiensis,* all eggs and juveniles are killed when exposed to 40 °C for 7 days, 50 °C for 5 min (LaMondia and Brodie, 1990) 58-59 °C for 30 minutes (Evans, 1991) and 65 °C for 30 min and 60 min (Holgado et al 2013). Cyst content of in wet cysts of *G. pallida* is killed at 80 °C in 1 min (LaMondia and Brodie, 1990; Stone and Wesley,

1975). Eggs and juveniles in dry cysts need higher temperatures and longer exposure times. The cyst content of dry cysts of *G. rostochiensis* is killed at 55oC in 47 days (LaMondia and Brodie, 1990), while eggs and juveniles of *G. pallida* require 90 °C for 1 min (Stone and Wesley, 1975). Due to the variability in lethal temperatures recorded in laboratory experiments and in field observations it seems that temperatures higher than 50 ˚C and wet conditions of more than one week would be required for the safe sanitation of PCN.

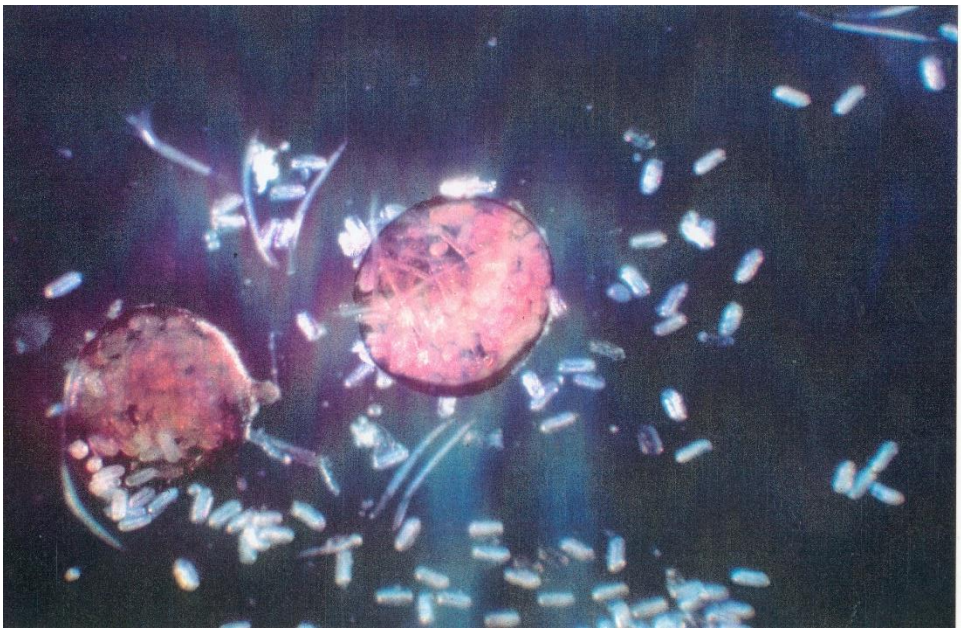

Figure 4. Potato cyst nematode *Globodera rostochiensis* showing one opened cyst with its content of eggs and juveniles. Photo: Bonsak Hammeraas, NIBIO.

Inactivation (i.e. loss of reproductive ability) of eggs in egg sacs of the root-knot nematode *Meloidogyne incognita* in full scale windrow composting required a temperature of 73 °C for four days. This also resulted in loss of infectivity of the nematodes, although no information was given on the temperature limit for reproductive failure (Hermann et al., 1994). It is assumed from expert judgement that these treatment conditions also are relevant for inactivation of both *M. chitwoodi* and *M. fallax.*

The temperatures reached in Nordic composting windrows and mattresses depend on the type of waste processed and type of structural material added (Christensen et al., 2002). Temperatures varied greatly within the systems of operation. During the sanitation phase the most critical points were at the top and at the base of the windrows. In the top position temperatures of 10-40 °C were recorded, while at the bottom temperatures of 30-45 °C (exceptionally 60 °C) were reached. In the central zone, temperatures during the sanitation phase varied between 40 and 75 °C. The temperatures reached during composting vary with the kind of waste processed and type of material added (Christensen et al., 2002).

There are conflicting reports on temperatures and exposure times required for sanitation of potato cyst nematode (PCN) in composting, with a variation from 40 to 50 °C for periods of 5 days up to one week (Bøen et al., 2006). In a study on windrow composting in Norway (Goffeng et al., 1978) it was shown that survival and infectivity of potato cyst nematode *Globodera rostochiensis* persisted in the outermost layer of the windrow with five turnings over 16 weeks. Hence, windrow composting may not meet the temperature requirements of +55 °C in the whole volume of material because of the cooling effects from the surrounding air (Goffeng et al., 1978). Also for *M. chitwoodi* a survival time of 13 days was reported in cooler parts of the windrow (Hermann et al., 1994; Witchuk et al., 2011). In addition to this type of cooling of windrow surfaces, there is also a cooling effect from the underlying ground as demonstrated in composting of pine bark infested with the pinewood nematode *B. xylophilus* in Portugal, where the process failed to reach the stipulated temperature of 56 ˚C for 30 min (EFSA, 2010).

It is difficult to conclude on a minimal number of turnings of a windrow or a mattress. Failure to reach 56 °C in windrow composting of pine bark as a control measure against pine wood nematode *Bursaphelenchus xylophilus* was recorded in Portugal when the windrow was turned twice (EFSA, 2010).

With regard to anaerobic thermophilic digestion few reports concern full-scale in-facility testing of nematodes. In Norway, Holgado et al. (2013) reported that PCN *G. rostochiensis* lost its reproductive ability in a pre-treatment pasteurisation step when exposed to 65 °C for both 30 and 60 min.

2.1.2 *Plasmodiophora brassicae*

The survival of *P. brassicae* in compost has been studied extensively, since is a serious threat to the cultivation of cabbage and because cabbage fields are amended with compost (Bollen and Volker, 1996). The survival of *P. brassicae* in compost has been reviewed by Noble and coworkers (2009), however, experimental data are not conclusive. Exposure to 60 °C for 1 day or 50 °C for 7 days in a high moisture regime was sufficient for eradication of the pathogen (Fayolle et al., 2006), but others have found that this may not be sufficient, depending on the strain of the pathogen. However, in general the pathogen appears difficult to consistently eradicate from compost, unless the temperature reaches 70 °C for at least 7 days and the compost is kept sufficiently moist (Christensen et al., 2001). In conclusion, the pathogen is likely to survive composting at 55 °C. Also, a treatment of waste at 70 °C for only 60 minutes may not be a guarantee for its eradication, but the number of viable propagules is usually greatly reduced if the moisture level of at least 40% is kept (Bollen and Volker, 1996; Philipp et al., 2005).

2.1.3 *Synchytrium endobioticum*

S. endobioticum is one of the most important pathogens of potato. It can be spread into the environment through discarded potato waste. Its resting sporangia (winter sporangia) are highly temperature tolerant and can remain viable in soil for over 40 years (Przetakiewicz, 2015). Therefore, they are suitable structures for testing and establishing eradication conditions during composting. Independent and carefully designed studies of survival in compost document the difficulty in finding a direct relationship betweenviability/infectiousness of winter sporangia and exposure to temperature over time (Kerins et al., 2018; Steinmöller et al., 2012; Steinmöller et al., 2007). They conclude that factors, other than solely time-temperature relationship, are operating in compost, such as differences regarding the presence of ammonia, organic acids and antagonistic microorganisms (Kerins et al., 2018). One of the complicating factors in assessing the survival of *S. endobioticum* is that pathogenicity tests can fail even when viable sporangia are present (Steinmöller et al., 2012; Steinmöller et al., 2007). Reliance on pathogenicity tests alone may have led to overly "optimistic" evaluations regarding kill-off conditions. In fact, Schleusner et al. (2019) suggest that only viable count in the microscope should be used to monitor survival. The discrepancy in results between pathogenicity tests and microscopic evaluation is thought to stem from the difficulty in controlling the germination of winter sporangia, i.e., in releasing the infectious zoospores (Schleusner et al., 2019).

When tested in mesophilic AD in a laboratory experiment, *S. endobioticum* easily retained viability, even when the digestate had been stored for several months after treatment. Mesophilic anaerobic digestion (MAD) treatment stimulated the release of winter sporangia from potato wart tissue, resulting in an increase of sporangia in the digestate over time (Schleusner et al., 2019). AD treatment usually involves a high build-up of ammonia, which is detrimental to this pathogen (Efremko og Yakoleva, 1981 – cited by Noble et al. (2009)) and this might contribute to its eradication from organic waste if anaerobic digestion was followed by a final pasteurization step (70 °C for 1 hour). However, more research needs to be done to understand if there is a practical way to quench the survival of *S. endobioticum*. Winter sporangia trapped in nylon gauzes and exposed to the chemical and microbial environment of composting at 55 °C for 21 days still yielded viable winter sporangia, and so did a heat treatment of winter sporangia, added to quartz sand in a semipermeable bag, which was suspended in compost, at 70 °C for 90 min (Steinmöller et al., 2012). Pasteurization in a water bath (70 °C) for 2 hours was also not sufficient to eliminate vital resting sporangia (Steinmöller et al., 2007). If the resting sporangia were dry, the time required to kill the propagules increased manyfold (from 15 min at 80 °C if wet to 90 min at 80 °C if dry).

Therefore, the treatments suggested in Terms of Reference 1 are not considered sufficient for the complete eradication of *S. endobioticum*.

2.1.4 *Olpidium* species

O. brassicae belongs to a group of biotrophic fungi with thick-walled resting spores (Bollen et al., 1989). These spores are resistant to heat and can survive in soil for more than 20 years (Maccarone, 2013). There are a number of *Olpidium* species that have herbaceous crops as host plants and they all serve as vectors for several plant viruses, as summarized by Maccarone (2013). *O. brassicae* is the vector of TNV (tobacco necrosis virus), which in itself is heat resistant (Bollen and Volker, 1996). *Olpidium virulentus* serves as vector for lettuce big-vein associated virus (LBVaV) and mirafiori lettuce big-vein virus (MLBVV), a complex of viruses that causes lettuce big-vein disease (LBVD). Composting of infected host plants (lettuce root clods) at a temperature range of 56-67 °C for 2-3 weeks resulted in a dramatic reduction of resting spores, but not in complete eradication, as a few resting spores remained in one of the 20 roots examined (Bollen et al., 1989). When *O. brassicae* was placed in onion waste in centres of flasks and subjected to 50 °C, no viable pathogen was retrieved after 7 days (Coventry et al., 2004). However, it is not clear whether oospores or zoospores of *O. brassicae* were monitored.

No literature records have been found on the fate of *Olpidium* species after AD. However, thermal inactivation points for this pathogen were established in laboratory experiments, both for zoospores (Campbell and Lin, 1976) and resting spores (Campbell and Grogan, 1964). For resting spores, the thermal eradication required temperatures above 50 °C, but probably closer to 65 °C for 10 min (Campbell and Grogan, 1964). For zoospores, eradication occurred between 40 °C and 45 °C for 10 min (Campbell and Lin, 1976). Autoclaving of potting mixture three times at 121 °C for 40 min was effective in killing both resting spores of *O. virulentus* and its associated viruses (Maccarone et al., 2010).
Olpidium spp. Are considered serious pathogens, since they survive for long periods of time in the field and transmit several virus diseases. In summary, heat-resistant resting spores of *Olpidium* may well survive the composting conditions specified in ToR1, as evidenced by (Bollen et al., 1989) but more studies are needed. A pasteurization step (70 °C for 1 hour) may not be sufficient for eradication of this pathogen since resting spores may be protected in the treated plant material, but it is safer than composting as such. Therefore, the treatments suggested in Terms of Reference 1 may not be sufficient for the complete eradication of this pathogen, depending on the presence of resting spores.

2.1.5 *Fusarium* species

Species of *Fusarium* are well known for producing mycotoxins, which makes their presence in food and feed important for food safety. Members of *Fusarium* are also known to be relatively heat tolerant (Noble and Roberts, 2004). For example, wheat seeds that were infested with *Fusarium graminearum* were recommended a dry treatment at 70 °C for 5 days to ensure the eradication of the pathogen prior to sowing (Gilbert et al., 2005). Results from composting experiments of different *Fusarium* species vary, but generally, if the temperature reaches 55 °C for a period of 3-7 days, the pathogen is usually eliminated (Chakroune et al., 2005; Coventry et al., 2004; Suárez-Estrella et al., 2003). It is during the thermophilic phase/heat phase (50-70 °C) of composting that eradication takes place (Bollen et al., 1989; Chakroune et al., 2005). However, if the composting process fails and the temperature is not sufficiently high, as in one experiment of six where different formae speciales of *Fusarium oxysporum* were tested, propagules can survive (Bollen et al., 1989). Another example of the resilience of *Fusarium* in compost is when eradication of *F. oxysporum* f.sp. *lycopersici* from compost seeded with infected kernels required 21 days at 65 °C (Christensen et al., 2001). When conditions of MAD (37.5 °C) were combined with a pasteurization step (treatment at 70 °C for 1 hour), *Fusarium culmorum* in feedstock could be eliminated (Henry et al., 2013). By using MAD conditions alone, without a pasteurization step, at least 6 days were required for the eradication of *Fusarium* species (Bandte et al., 2013; Henry et al., 2013).

In summary, composting at 55 °C for three weeks will in most cases be sufficient for the eradication of *Fusarium* species, but these conditions cannot guarantee its eradication, as exemplified by Noble and Roberts (2004), where composting at even higher temperatures (53-65 °C, 65-74 °C) for a three-week period did not suffice. Heat treatment at 70 °C for 1 hour can probably ensure the elimination of *Fusarium* if the organic matter is kept moist, particularly if this step is combined with MAD (Henry et al., 2013).

2.1.6 *Sclerotinia* species

Sclerotinia sclerotiorum is the species of *Sclerotinia* that is extensively studied. Its sclerotia are resistant structures which enable the fungus to survive adverse conditions. Even so, sclerotia are sensitive to the temperatures reached during composting if the substrate is sufficiently moist. For example, Bollen et al. (1989) reported complete inactivation of sclerotia of *S. sclerotiorum* after a 2-3-week heat phase (>40 °C) during composting. Inactivation was assessed as absence of symptoms on cucumber seedlings that had been planted in composted residues. Therefore, *S. sclerotiorum* has been regarded as easier to eradicate during composting than first expected (Bollen and Volker, 1996; Noble, 2011; Noble et al., 2011a; Noble et al., 2009). However, the temperature sensitivity of *S. sclerotiorum* is much lower during dry conditions, which also is true for other pathogens, e.g. *G. rostochiensis* and *S. endobioticum* (Bollen and Volker, 1996). Longer exposure time at the same temperature was required when sclerotia were dry than when they were water saturated (van Loenen et al.,

2003). Sclerotia exposed to dry heat required a treatment at 120 °C for a period of 20 min for inactivation, whereas water-saturated sclerotia completely lost viability after 20 min at 50 °C (Morall, unpublished; cited in Dueck et al. (1981)). The viability of sclerotia of *S. sclerotiorum* in static compost piles was studied by Downer et al. (2008) and it was considered one of the most persistent plant pathogens that they studied (they studied: *Armillaria mellea, Phytophthora cinnamomi, S. sclerotiorum* and *Tylenchulus semipenetrans*). The authors suggested that the reason for this was an effect of the piles not being turned. Turning would have stimulated microbial antagonism and the production of inhibitory chemicals sensed by the fungus during aerobic composting.
Few reports exist on the viability of *S. sclerotiorum* after MAD (35-42 °C), but in one study, viability was lost after 6 hrs (Bandte et al., 2013). It was not clear whether sclerotia or mycelium was used as inoculum in the experimental digesters of this study. However, when examining the response of a close relative to *S. sclerotiorium*, namely, *Sclerotium cepivorum (*Xu et al., 2010), the sclerotia remained viable, at least in part, even after a 21-day-long treatment with MAD (35-40 °C) (Termorshuizen et al., 2003).
In summary, for *Sclerotinia* species, the presence of water is crucial for their inactivation. If the substrate/feedstock is not kept moist throughout the heat treatment at 70 °C for 1 hour or during composting, the sclerotia will remain viable, since dry sclerotia will only be affected if the temperature reaches 120 °C. On the other hand, if the feedstock is kept moist (see for example, van Loenen et al., 2003), the treatments described in Terms of Reference 1 will most likely be effective in eliminating *Sclerotinia* inoculum.

2.1.7 *Phytophthora* species

A study assessed the survival of *Phytophthora cinnamomi* after 8 weeks in fresh green waste (FGW) and aged green waste (AGW). The fresh waste was least favorable for survival of *Phytophthora*. The authors proposed that the lower survival rate in FGW was due to the higher temperature recorded in FGW (70 °C) than in AGW (45 °C) (Downer et al., 2008). Indeed, survival of oospores of *P. capsici* in moistened soil was an effect of temperature and time of exposure; only 1 hour was required for eradication at 53 °C whereas 199 hours were required at 40 °C. The oospores were almost unaffected at temperatures below 36 °C (Etxeberria et al., 2011). In mesophilic AD conditions (37 °C), the number of propagules of *P. capsici* were reduced but not eliminated over the course of 22 days (3 weeks) (Chen et al., 2016), which agrees with the compost studies (Downer et al., 2008) in that this temperature is too low for ensuring eradication of *Phytophthora* species. But in another study, *P. ramorum* did not survive after two weeks of composting at 55 °C (Swain et al. (2006)).
Even if temperature and length of exposure clearly are important, however, other factors affect the survival of *Phytophthora* propagules. During AD, substrates rich in nitrogen generate ammonia because of the relatively high pH of the digestate. The germination of propagules of

P. cinnamomi and *Phytophthora parasitica* were inhibited in soil already at low levels of ammonia (Tsao and Oster, 1981). Thus, accumulation of ammonia can be an important factor in the growth-suppression of *Phytophthora* species during AD (Henry et al., 2013). Zoospores of *Phytophthora ramorum* were tested for survival in different finished composts, which had completed their thermophilic phases at the time of pathogen introduction. Fresh compost (thermophilic phase completed less than a week before) was less favorable for survival than mature compost (aged 4 weeks or more). The pathogen was recovered at high rates from all composts tested; in equal numbers from windrows and forced air static pile composts. The reason for the discrepancy in survival rate in composts of different maturity is unknown, but the authors propose that it can be either the residual survival of thermophilic microorganisms or the presence of antimicrobial compounds in the young compost (Swain and Garbelotto, 2015). In fact, numerous reports document that composting generates an environment rich in antagonistic microorganisms and antimicrobial chemicals that contribute to suppressing the survival of *Phytophthora* species.

In summary, treatment at 70 °C for 60 min should probably suffice for killing off *Phytophthora* species, but there were no records that actually proved this. Composting at 55 °C for four weeks should also suffice, but only if this temperature can be assured throughout the compost matrix over time. The composition of different composts may affect the time-temperature for eradication, and this is why compost reports on *Phytophthora* show different results.

2.1.8 *Clavibacter michiganensis* ssp. *michiganensis* (*Cmm*) and *Clavibacter michiganensis* ssp. *sepedonicus* (*Cms*)

Composting of tomato stems that were naturally infested with *Cmm* required 130 days, i. e. fully mature compost, for bacterial levels to reach zero. The process was completely aerobic, with a thermophilic phase (>45 °C) of approx. 70 days, followed by a mesophilic phase (Raviv et al., 2010). In contrast, when dried tomato stem pieces were suspended in nets in the air in a hot greenhouse (20-60 °C), *Cmm* was not detectable after 10-14 days (Shlevin et al., 2004). Like the situation in compost, *Cmm* in tomato debris that were moist from having been buried in soil required 4 weeks at 45 °C for eradication (Zanón and Jordá, 2008). *Cms* also survived composting well; it survived a period of 21 days, when the temperature exceeded 55 °C for 13 days. *Cms* was added as a suspension to ready-made mould compost (Steinmöller et al., 2013). However, when *Cms* was inoculated into potato tissue that was exposed to a hot water bath, the bacteria did not survive for very long: 6 hours at 60 °C resulted in complete eradication (Stevens et al., 2021). Kaemmerer (2009) demonstrated that *Cms* was more thermotolerant in heat-treated digestate than in a heat-treated buffer solution. Turner et al. (1983) demonstrated that *Cmm* was completely eradicated during anaerobic digestion at 35 °C for 7 days. These findings were confirmed by Henry et al.

(2013) for *Cms,* since AD at 37.5 °C for 6 days rendered the pathogen undetectable by using bio-PCR.

In conclusion, *Cmm* and *Cms* are temperature sensitive when they are residing in exposed plant material (such as bags in the air or in water bath conditions). Two studies suggested that mesophilic AD conditions for a week would be sufficient for their eradication. The effect of composting is more complex. Complete eradication requires long periods of time and high temperatures (> 3 weeks at 55 °C). However, compost is in itself suppressive to *C. michiganensis* (Kasselaki et al., 2011; Utkhede and Koch, 2004; Yogev et al., 2009).

2.1.9 *Ralstonia solanacearum (Rs)*

The eradication conditions required for *R. solanacearum* are somewhat similar to those for *C. michiganensis* in that both pathogens are eradicated after treatment for 1 hour at 60 °C suggesting that pasteurization for 1 hour at 70 °C should render the substrate safe. These bacterial pathogens are also both quite sensitive to AD conditions (for *Rs*, see below) (Ryckeboer et al., 2002; Termorshuizen et al., 2003), and to heat exposure when treated in isolated plant parts at 55 °C (Henry et al., 2013). Eradication conditions for *Rs.* in compost are not well-established. However, the survival of *Rs.* in compost is highly dependent on moisture levels and type of compost (Mengesha et al., 2017; Tomlinson et al., 2011). In thermophilic AD (52 °C) conditions, *Rs.* was eradicated after 6-12 h, depending on inoculum density; longer time period was required when a higher inoculum density was used (Ryckeboer et al., 2002). When mesophilic conditions were used in AD (40 °C), 6 weeks were required to reach undetectable levels of *R.s.* in infected garden vegetable substrate (Termorshuizen et al., 2003). A period of three weeks (22 days) of mesophilic AD (37 °C) reduced the detectable levels of *Rs.* to some extent but was not sufficient for its eradication in inoculated tomato plant waste (Chen et al., 2016).

2.1.10 Japanese knotweed (*Reynoutria japonica*)

Limited information exists for the fate of Japanese knotweed (Figure 5) after composting or AD. The few studies that exist suggest that both composting and AD could be ways to utilize its above-ground plant biomass in the future, without risking the spread of this invasive species. The ease with which it can spread (0.7 g of rhizome fragments are sufficient for generating new plants) is the reason why researchers and municipal waste authorities are hesitating in recommending composting. Day et al. (2009) determined that composting of different plant parts for 3 days at 55 °C resulted in lack of germination. However, Bollens (2005), recommended composting at a minimum of 70 °C. A study on mesophilic AD of stem fragments of Japanese knotweed (37 °C for 40 days) showed that these propagules can be completely inactivated through anaerobic digestion at these temperatures (Van Meerbeek et al., 2015). Nevertheless, in the UK and in Sweden, composting of Japanese knotweed is

prohibited. Plant waste has to be burned. This may be due to the sturdiness of the rhizomes, which are massive in width and length, and partly lignified, which possibly could allow them to pass unscathed through anaerobic digestion or composting (Figure 6).

Figure 5. Japanese knotweed (*Reynoutria japonica*) is a fast-growing plant that outcompetes native plants and can form thickets of large monocultures. Photo: Sandra A. I. Wright

Figure 6**.** The sturdy, dense crown at the base of detached canes hint to the woody nature of mature rhizomes of Japanese knotweed under the ground, which can be as thick as 5 cm in diameter. Photo: Daniel M. Wright

2.1.11 Giant Hogweed (*Heracleum mantegazzianum)*

Very little information exists for Giant Hogweed (Figure7), an invasive plant species that is mainly propagated through seeds (Page et al., 2006). There are no reports on composting of seeds. The AD study performed by Van Meerbeek et al. (2015) on Japanese knotweed also included seeds of Giant Hogweed. The result was the same as for Japanese knotweed, i. e. no viable seeds of Giant Hogweed were recovered after mesophilic AD (37 °C for 40 d). Subjecting seeds to heat treatment in water baths (35 and 42 °C) was used to mimic conditions in biogas reactors. The result was that at 35 °C a minimum of 8 days was required for complete loss of seed viability, but at 42 °C, only 2 d were required (Tanke et al., 2019). There is still much to learn here, for example, about the reaction of seeds of Giant Hogweed to higher temperature regimes and whether the time in AD can be shortened, since 40 d is a very long time and not realistic in flow-through systems, which are the most commonly-used biogas reactors (Tanke et al., 2019).

There are too few reports to make a solid assessment on the possible risk of survival of seeds after composting or heat treatment at 70 °C for 60 min (Terms of Reference 1), but from the limited information available, it appears as if pasteurization (70 °C for 1 hour) or

MAD are possible routes for its elimination, which in turn also would suggest that composting at 55 °C for 4 weeks might lead to inactivation, however more studies are needed to confirm this. There is a lot of uncertainty in this conclusion, due to the limited number of studies performed on Giant Hogweed.

Figure 7. Giant Hogweed (*Heracleum mantegazzianum*). Seeds that fall to the ground can initiate colonies in new areas, through the dumping of infested soil in new areas, for example during road construction. Photo: Sandra A. I. Wright

2.1.12 *Echinochloa crus-galli*

This weed species can be of practical importance in composting and AD, since it can be present in cow manure as it passes through the digestive tract of cows (Šarapatka et al., 1993; Wiese et al., 1998). Composting of manure can be a means of reducing the number of viable seeds. Composting was tested at three different temperatures (49, 60, 72 °C) over several days. The lowest temperature that resulted in complete elimination of seed viability was 49 °C for a period of 3 days (Wiese et al., 1998). A heat treatment experiment that was

supposed to simulate solarization reported that it took 0.17 h at 70 °C, 0.25 h at 60 °C, 9 h at 50 °C and 16 h at 46 °C to kill off all seeds. At temperatures below 46 °C, viability was not affected (Dahlquist et al., 2007). In an AD experiment, maintaining seeds of *E. crus-galli* for 1 month at a depth of 40 cm where the temperature was 30 °C permitted 36% of the seeds to survive (Šarapatka et al., 1993). In contrast, seeds of *E. crus-galli* mixed with substrate in bags and subjected to MAD at 37 °C for 30 days were not viable (Westerman et al., 2012). In the same study, ensiling for 46 days resulted in 0.15% viability of the seeds. The conclusion is that composting at least at 49 °C appears to be a good strategy, since exposure to temperatures below 46 °C did not affect viability. In the case of AD, a thermophilic process would be desirable. In addition, pasteurization (70 °C for 1 h) is probably successful for sanitation, judging by the results of in vitro experiments by Dahlquist et al. (2007), see above.

2.1.1 *Avena fatua*

Wild oats (Avena fatua L.) are widely spread and constitute a weed problem in Norway. According to the Norwegian regulation on wild oats, soil products should be free, or contain seeds that cannot germinate, from *A. fatua* before sales (LMD, 2015).

A study by Blackshaw and Rode (1991) showed that viability of seeds declines during passage through the digestive tract of animals. Johansen et al. (2013) showed that thermophilic conditions (55 °C) for 2 days was enough to receive complete mortality for *A. fatua*. In the same study Johansen et al. (2013) also showed that at mesophilic conditions, seeds of *A fatua* completely lost germination. Furthermore, *A. fatua* seeds has been shown to be not viable after mesophilic conditions (37°C for 7 days) in a biogas plant (Leonhardt et al., 2010; Weinhappel et al., 2010).

2.1.2 Viruses

Plant viruses are composed of a nucleic acid that is protected by a coat consisting of proteins and, in the case of some virus groups, a lipid membrane. Viroids are a group of naked circular RNA particles that in many ways behave like viruses, however they do not contain a protein coat. They are highly infective and are easily transmitted mechanically, and, due to their ability to form secondary structures, they are considered relatively heat-resistant. Viruses and viroids require living cells to be able to multiply and most viruses are transmitted from one plant to another by vectors which can be insects such as aphids, whiteflies or thrips, nematodes, or fungi/plasmodiophorids (*e.g., Olpidium* or *Spongospora*). At the same time, most viruses can be transmitted mechanically, meaning that free virus particles can infect living plants through wounds, however the ability to be mechanically transmitted greatly varies between virus species. Tobacco mosaic virus is considered as one of the most easily mechanically transmitted viruses (Scholthof et al., 2011) and is also considered one of

the most heat-stable viruses known. Finally, some viruses can be transmitted through seeds from the plant to its offspring.

During composting, it is assumed that all green plant tissues will be killed, and also insect vectors will most probably be killed. For nematodes, it is well-known that *e.g.,* tobacco rattle virus is able to survive for several years in the vector populations, protected by nematode survival structures (cysts) (Cadman and Harrison, 1959). Furthermore, some of the virus-transmitting fungi/plasmodiophorids are able to form spores that can survive in soils for many years. Therefore, survival of vector-borne viruses in compost is highly dependent on the survival of the vectors, i.e. nematodes and spores of fungi/plasmodiophorids), and therefore, first of all, the survival of the vector must be considered. Similarly, the survival of seeds will also most likely determine the survival of seed-borne viruses. However, some heat-resistant and highly mechanically transmissible viruses such as TMV may also pose a risk of survival in compost as free particles, and they could also potentially infect new hosts when the compost is used.

Traditionally, viruses have been characterized by their thermal inactivation point, and thus this parameter can be retrieved from virus databases and at least a comparative estimate of the heat-resistance of a given virus is given. Viruses such as tomato spotted wilt virus having a lipid membrane are rather heat sensitive (inactivation at 46°C for 10 minutes) (Roggero and Pennazio, 1997) and will most likely not survive composting, whereas TMV is considered one of the most heat-resistant viruses. It should further be noted that microbial/enzymatic degradation and not only the temperature itself is most probably an important factor during composting, particularly for free virus particles that are not protected by a vector or by living plant material (Noble and Roberts, 2004).

Most studies of the ability of viruses to survive composting have been performed using TMV as a model organism. This virus belongs to the tobamoviruses that are heat-resistant, are easily transmitted mechanically, and are generally easy to multiply in a number of host plants. However, studies including other viruses that tobamoviruses have been performed. Melon necrotic spot virus, tobacco necrosis virus and tomato spotted wilt virus could be eradicated by a composting temperature of 65 °C for up to 28 days (Noble and Roberts, 2004; Suarez-Estrella et al., 2002), whereas infectivity of lettuce big vein virus and tobacco necrosis virus inside *Olpidium* could be eliminated by composting at 50 °C for 7 and 50 days, respectively (Coventry et al., 2002). Cucumber green mottle mosaic virus, pepper mild mottle virus, TMV and tobacco rattle virus were found to be more temperature resistant (Avgelis and Manios, 1992; Christensen et al., 2001; Hermann et al., 1994; Hoitink and Fahy, 1986; Menke and Grossmann, 1971; Ryckeboer et al., 2002). Conditions for eradication of TMV varied, but temperatures over 66 °C and composting periods more than 28 days

generally resulted in elimination of the virus (Christensen et al., 2001; Hermann et al., 1994; Hoitink and Fahy, 1986; Ryckeboer et al., 2002) reported elimination at 78 °C for 57 days of incubation, but no survival was reported after 26 weeks at lower temperatures (31 °C).

Viroids are considered relatively heat resistant, but not much literature exists on the survival during composting. However, Kerins et al. (2018) found that potato spindle tuber viroid (PSTVd) was undetectable by bioassays and PCR tests following exposure to compost for ≥28 days at ambient temperatures, and for more than 7 days at 50 °C, regardless of the moisture content of the compost.

2.1.3 Spanish slug (*Arion lustanicus*)

Spanish slug (*Arion lustanicus*) has received a lot of attention with respect to plant damage and reproductive capacity at different low temperature scenarios (2-20 °C) (Slotsbo et al. 2013) as well low temperature threshold for survival (death) (-3 °C) (Slotsbo et al., 2011). Highly significant interactions were stated between ambient temperature (minimum and maximum) and survival of Spanish slug (Dörler et al. 2018). Despite of this, impressively little attention was given with respect to the impact of high temperature corresponding to mesophilic or thermophilic conditions under either aerobic or anaerobic conditions. Several popular science and one scientific (Dörler et al. 2018) studies report on sheltering function of garden composts for slugs, among these Spanish slug. However, these observations do not consider the impact of the process on life cycle functions of the organism. According to impact studies of digestates and composts on various slugs, the presence of molluscicidal effects during the processes might not be excluded (Speiser, 1998). However, there is a considerable need to study this in detail.

2.1.4 Conclusion on the survival of harmful alien organisms

Summary of effects of treatments described in ToR1 on selected potentially harmful organisms and groups of organisms are presented in table 9.

2.1.4.1 Nematodes

PCN, *G. rostochiensis*, *G. pallida* and PWN *Bursaphelenchus xylophilus* are moderately likely to survive and remain infective after windrow composting where the temperature of the windrow is at least 55 °C for four weeks. The temperature variations are variable throughout the windrow as well as in matrasses, and cold sones would allow for survival (Goffeng et al. 1978, Hermann et al. 1994, EFSA 2010). The conditions are moderately unfavourable compared to the tolerance of the pest. This statement has a medium uncertainty because some information is missing or some data are missing, incomplete, inconsistent or conflicting. The root-knot nematodes *Meloidogyne* spp. are likely to survive and remain

infective, because eggs in egg sacs are insensitive to the exposing conditions as specified in ToR1. This statement has a medium uncertainty, because some information and data is missing. The effect of a treatment at 70 °C for 60 minutes with a max particle size of 12 mm will vary according to pest species. With regard to *G. rostochiensis*, *G. pallida* and *Bursaphelenchus xylophilus* the likelihood of survival is considered low because the pests are particularly sensitive to the exposing conditions and the exposure time is long compared to the tolerance of the pests. The statement has a low uncertainty, because no or few data are missing, incomplete, inconsistent or conflicting. No subjective judgement is introduced. No unpublished data are used. For the root-knot nematodes *Meloidogyne* spp. the likelihood of survival and infectivity is moderate because the pest is moderately sensitive to the exposing conditions and the exposure time for four weeks is moderately long compared to the tolerance of the pest. The uncertainty of this statement is medium because some information and data is missing. Subjective judgement is introduced with supporting evidence.

2.1.4.2 Protozoa

Experimental data on the viability of *P. brassicae* with regard to time-temperature of exposure are not conclusive. *P. brassicae* has been one of the most commonly used as an indicator organism during AD (Westerman and Gerowitt, 2013). It has in the past also been suggested as a phytosanitary indicator organism for compost, as reviewed by Witchuk et al. (2011). However, it was deemed unsuitable as an indicator organism for compost, due to its high survival rate during both moist and dry conditions (Noble et al., 2011a). The probability for its survival in compost according to conditions of ToR 1 are high and the uncertainty is medium.

2.1.4.3 Fungi, fungal-like organisms and bacteria

Winter sporangia of *S. endobioticum* have a high probability of survival after the treatments specified in ToR1. The level of uncertainty is low. The key issue here is whether or not it is infectious. Pathogenicity tests are elusive, since they often fail despite the use of viable winter sporangia. *Olpidium* species probably do not survive the pasteurization treatment (70 °C for 1 hour) specified in ToR 1, but they could survive the composting conditions described in ToR1.1, since they have been reported to survive composting when 56-67 °C is maintained for 3-4 weeks. The level of uncertainty is high, since composting literature is scant; and none was retrieved for MAD. Most studies carried out on different species of *Fusarium* have indicated that the number of propagules diminish after composting for several weeks or after MAD. All results do not point in the same direction, however, since in some cases *Fusarium* species have proven difficult to completely eradicate by composting (Christensen et al., 2001). When a pasteurization step (70 °C, 1 hour) was included in combination with MAD and the feedstock was kept moist and homogeneous, chlamydospores of *F. culmorum* and *F. oxysporum radicis-*

lycopersici were undetectable (Henry et al., 2013). Therefore, a pasteurization step would ensure eradication of *Fusarium* species from the organic material with a high probability and low levels of uncertainty. There is a high probability that sclerotia of *Sclerotinia* species can be inactivated by the treatments described in ToR 1 are employed, but only if the feedstock is kept sufficiently and consistently moist. There is no specific level of moisture, but this conclusion is based on the great insensitivity of dry sclerotia to the same temperature that would reduce or eliminate the pathogenicity of moist or damp sclerotia (van Loenen et al., 2003). The level of certainty is medium to high. The viability of sclerotia have mostly been studied in compost and not much in MAD conditions, so most data available originate from compost studies. It is important to maintain stable and high temperatures (>53 °C) during composting in order to eradicate *Phytophthora* species. In aged compost or during MAD, the temperature may not be sufficiently high (40-45 °C) for killing off all propagules, even after several weeks. The probability is high and the level of certainty medium. If a hygienization step is included, the probability of eradication is high, with low uncertainty. The bacterial pathogens, *Cmm*, *Cms* and *R. solanacearum,* are most probably destroyed during conditions specified in ToR 1, but as for many other pathogens, the compost has to be turned, be kept sufficiently moist throughout and a high temperature (55 °C) ensured for the duration of the treatment. The level of uncertainty is medium. Pasteurization (70 °C for 1 hour) is regarded as an efficient method for the eradication of bacterial pathogens.

2.1.4.4 Plants

For the three plant species evaluated, there is very little information about their survival after thermal treatment. In the case of the invasive plant species, Giant Hogweed (*H. mantegazzianum* and Japanese knotweed (*R. japonica*), dissemination of plant material in any way (during transit or at the treatment facility) is regarded as a risk to the biodiversity of native flora. Therefore, even if the few reports available suggest that propagules of both could be destroyed during MAD and exposure to high temperatures, extreme caution should be taken. The level of uncertainty is high for all three plant species (*R. japonica, H. mantegazzianum* and *E. crus-galli*), since tests have not been carried out under the specific treatment conditions described in ToR 1. One exception is the study which demonstrated that pasteurization at 70 °C was effective even after 0.17 h for *E. crus-galli* (Dahlquist et al., 2007).

In Appendix IV we list the forty-four-woody vascular plant species on the Norwegian Alien Species List (2018) as "particularly high risk". The plants assessed in this report represents the most difficult ones to eliminate via the processes mentioned in the ToR's. Generally, all plant parts will be fully digested via the processes as well as seeds. Only very hard seeds might survive mesophilic processes. The level of uncertainty is high for all of the forty-four plants.

2.1.4.5 Viruses

TMV or other tobamoviruses are some of the most heat-resistant plant viruses and are thus considered as among the hardest to eliminate. Conditions for TMV inactivation are reported to be well above 60 °C for more than 4 weeks and thus temperatures of 55 °C for 4 weeks, as mentioned in the ToR 1, are unlikely to inactivate the virus. The level of uncertainty is low, since the behavior of this virus during composting is well-studied. For other tobamoviruses, the level of uncertainty is medium. TMV is not destroyed during heat treatment at 70 °C, at 75 °C nor at 80 °C for 1 hour (Bollen and Volker, 1996; Philipp et al., 2005). Thermophilic anaerobic digestion followed by composting at 58 °C was reported to eliminate TMV (Ryckeboer et al., 2002). The level of uncertainty is medium, since only few studies have examined the behavior of TMV or other viruses during AD. For viruses that are vector-transmitted, the survival of the respective vector and its survival structures (*e.g.,* resting spores) must be assessed.

Table 9. Summary of effects of treatments described in ToR1 on selected potentially harmful organisms and groups of organisms. The basis for the assessment is variable with respect to numbers of organisms.

Pest	**Composting in windrows (> 2.5 m) or mattresses where the temperature of the windrow is at least 55 °C for four weeks and the windrow is turned at least three times during this period**		**Treatment at 70 °C for 60 minutes with a max particle size of 12 mm whereby this is achieved in a composting process or as a pretreatment step before an anaerobic treatment process**	
	Probability of survival	**Uncertainty**	**Probability of survival**	**Uncertainty**
Nematodes				
Bursaphelenchus xylophilus	Moderately likely	Medium	Unlikely	Low
Globodera rostochiensis	Moderately likely	Medium	Unlikely	Low

Pest	**Composting in windrows (> 2.5 m) or mattresses where the temperature of the windrow is at least 55 °C for four weeks and the windrow is turned at least three times during this period**		**Treatment at 70 °C for 60 minutes with a max particle size of 12 mm whereby this is achieved in a composting process or as a pretreatment step before an anaerobic treatment process**	
Globodera pallida	Moderately likely	Medium	Unlikely	Low
Meloidogyne spp	Likely	Medium	Moderately likely	Medium
Protozoa				
Plasmodiophora brassicae	Likely	Medium	Moderately likely	High
Fungi				
Synchytrium endobioticum	Resting spores will likely survive	Low	Likely	Low
Olpidium brassicae	Resting spores will likely survive	Medium	Unlikely	Medium
Fusarium spp	Unlikely	Low	Unlikely	Low
Sclerotinia spp	Unlikely in wet compost. Likely in dry compost	Medium	Medium	Medium

Pest	Composting in windrows (> 2.5 m) or mattresses where the temperature of the windrow is at least 55 °C for four weeks and the windrow is turned at least three times during this period		Treatment at 70 °C for 60 minutes with a max particle size of 12 mm whereby this is achieved in a composting process or as a pretreatment step before an anaerobic treatment process	
Fungal-like organisms				
Phytophthora spp	Unlikely	Low	Unlikely	Low
Bacteria				
Clavibacter michiganensis ssp. *michiganensis* and *C. m. sepedonicus*	Moderately likely	Medium	Unlikely	Medium
Ralstonia solanacearum	Moderately likely	Medium	Unlikely	Medium
Plants				
Japanese hogweed	Above-ground parts unlikely. Rhizomes likely	Medium	Above-ground parts unlikely. Unknown for rhizomes	Medium
Giant hogweed	Unlikely	High	Unlikely	High

Pest	**Composting in windrows (> 2.5 m) or mattresses where the temperature of the windrow is at least 55 °C for four weeks and the windrow is turned at least three times during this period**		**Treatment at 70 °C for 60 minutes with a max particle size of 12 mm whereby this is achieved in a composting process or as a pretreatment step before an anaerobic treatment process**	
Echinocloa crus-galli	Unlikely	High	Unlikely	High
Avena fatua	Unlikely	Low	Unlikely	Low
Viruses				
	Unlikely for most viruses. However, viruses vectored by fungi (and fungi-like organisms) such as *Olpidium* or *Spongospora* may survive inside resting spores	Medium	Unlikely for most viruses. However, viruses vectored by fungi (and fungi-like organisms) may survive inside resting spores	Medium

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2.2 Assessment of validation methodology

The validation methodology relevant for composting and anaerobic fermentation is based on the animal-byproduct regulation. The purpose of this regulation is to avoid risks that may originate from residual animal products that are not used for human consumption. It thus focuses on human and veterinary public health and prevention of dissemination of zoonotic diseases. The suggested process validation for these purposes focuses on zoonotic organisms, and in consequence the choice of indicator organisms.

Traditional sanitary assessment, used in context of food safety assessment, hygienic quality of potable and environmental water as well as organic fertilizers, is based on index and indicator organisms, i.e., "…a group or species indicative of pathogen presence and behavior, respectively…" (Gerba, 2009). *Escherichia coli* (not mentioned in the terms of reference), *Salmonella*, enterococci and, eggs of *Ascaris suum* are examples for indicator organisms. Absence of these indicator organisms post process verifies the safety of the product. For determination of thermal inactivation, the D-value is used as a measure to define the time or dosis required to reduce the indicator organisms by one log, thus a reduction of 90%.

Feedstock groups defined for this report may contain animal products which were meant for human consumption, but which were wasted (*e.g.*, kitchen waste incl. plate scrapings, wastes from food processing facilities). As such, their safety has been verified with respect to zoonotic hazards.
Furthermore, the present evaluation considers;
(i) plant and animal wastes meant for human consumption as well as plant and animal wastes not meant for human consumption (manure, bulking material)
(ii) plant wastes originating from environmental horticulture (such as urban greening incl homegardens), processing industry for food and feed.
Although plants may be contaminated by human pathogens, plants do not display a primary host. In the present context of AD and composting of organic wastes, the purpose of assessment is the validation of efficacy towards plant pathogens.

Thus, criteria for an ideal indicator organism have to meet the conditions in AD and composting as illustrated in Figures 2 and 3. Here, temperature, humidity and exposure time as well as feedstock composition are essential factors to be considered. Thus, the listed indicator organisms are only relevant, if they have survival probabilities similar to, or greater, than those of the plant pathogens to be eliminated. They also should reflect the target organisms' reproduction capacity.

Criteria for relevant validation organisms

The purpose of the validation is imperative for the choice of validation method, *e.g.,* sanitary aspects (presence or absence of fecal contamination), evaluation of treatment or process efficacy. Relevant criteria, that such an ideal indicator organism must meet, are summarized in Table 10.

Table 10. Criteria for an ideal indicator organism[1] with respect to inactivation of plant pathogens and pests through AD and composting

Criteria
• The organism should be useful for all type of feedstocks.
• The organism should be present whenever a plant pathogenic or pest organism is present.
• The organism should have a longer survival time than the hardiest plant pathogenic and pest organism that may be present in the feedstock and with respect to the process specific conditions.
• The organism should not grow in the feedstock during the AD and compost process.
• The testing method should be easily performed.
• The density of the indicator organism must be correlated to the presence of potential plant pathogenic or pest organisms.

[1] indicator organisms are defined as "…a group or species indicative of pathogen presence and behavior, respectively…" (Gerba 2015)

From the set criteria it becomes obvious, that there is no universal indicator organism, mimicking all potential plant pathogenic or pest organisms that might be present in post process. In practice, it would be nearly impossible to identify one indicator organism that is representative of all plant pathogens or pests, since the survival patterns of different organisms from different kingdoms even at the same environmental conditions are different. Therefore, a number of different organisms must be included in a quality assessment system (validation methodology).
Furthermore, the adequate detection technology should make a clear statement about 'dead or alive' cells and ability to reproduce. This excludes organisms engaging into metabolically inactive stages, such as viable but non culturable (VBNC) or persister cells.

As the indicator organisms listed in the ToR are not likely to be present in the feedstock in sufficiently high numbers, they can only be used for verification, if they are added to the

feedstock prior to the process. However, there are two general issues to take into account before going deeper into the validation of existing methodologies:
1) Inoculation of the listed indicator organisms into the feedstock prior to treatment: It is questionable if contamination of the feedstock with human pathogens is a suitable procedure.
2) The biggest risk for dispersal of plant pathogens from insufficiently hygienized composts and residues from biogas facilities are plant-based feedstocks, *e.g.,* park and garden wastes, wood-based bulking material, waste products from plant-based processing industries, and plant-based kitchen wastes.

2.2.1 5 log10 inactivation of *Salmonella* Senftenberg (775W, H2S-negative)

Salmonella spp. is a facultative anaerobic gram-negative bacterium pathogenic to humans. *Salmonella* spp. is not particularly heat resistant (Silva and Gibbs, 2012). However, the *Salmonella* serovar Senftenberg 775W has been shown to be more heat resistant than other serovars (Davidson et al., 1966; Kwast and Verrips, 1982). Decimal reduction time of Salmonella Senftenberg (775W, H2S-negative) at 57 C and pH 6.8 was assessed to be 31 min. Cross response to stress was observed in a laboratory study when Salmonella Senftenberg was exposed to starving (Ng et al., 1969). No difference was observed during the early phase (80 min) of heat exposure. However, reduction in viable count was much quicker when the strain was exposed to nutritionally scarce conditions. The same study also demonstrated that heat resistance of Salmonella Senftenberg (775W, H2S-negative) is weaker when the strain starved from organic N than from organic C (Ng et al., 1969). In this context it is worthwhile to notice, that this study is based on culturability of Salmonella Senftenberg /775W, H2S-negative). The presence of "dormant" cells (viable, but non culturable) has been demonstrated for *Salmonella* sp ((Ou et al., 2021) and references therein). The results obtained by Ng et al. (1969) are not conclusive if *Salmonella* might have regained its vitality and virulence after the end of the experiment. Furthermore, nutrient rich rather than nutrient scarce conditions will be expected in feedstocks used in compost and biogas facilities, meaning that long reduction time is expected. In light of the higher heat tolerance of some of the plant pathogens, an analysis confirming the post process absence of *Salmonella* Senftenberg is therefore no guarantee of a satisfactory reduction of plant pathogens (see Table 11). Likewise, *E. coli* has been suggested as a validation organism for description of pathogen inactivation during composting since its inactivation pattern is very similar to *Salmonella* (Burge and Marsh, 1978; Farrell, 1993). However, biowaste typically contains plant pathogens that are more resistant than *E. coli* and validation organisms with higher heat resistance are therefore preferable.

2.2.2 5 log10 inactivation of *Enterococcus faecalis*

The genus Enterococcus consists of gram-positive streptococci that are mostly of fecal origin (*e.g., Enterococcus faecalis* and *E. faecium*). Studies have been carried out on the use of *Enterococcus* as validation organism for monitoring pathogen inactivation in treatments of wastewater (Lau et al., 2020). From these investigations it has been found that *Enterococcus* are useful validation organisms of pathogen inactivation during treatment of biowastes and could thus potentially also be useful as an indicator for plant pathogen eradication. Enterococcus are generally considered as reliable indicator organisms for validation of the sanitary process during composting (Déportes et al., 1998; Pereira-Neto et al., 1986). As enterococci are more resistant to temperature, chemical treatment, and desiccation (Lau et al., 2020) they are better suited for validation than *e.g., Salmonella*. The temperature resistance profile of enterococci compared to other pathogens (not plant pathogens) is generally high in animal biowaste (Bendixen et al., 1995). However, the elimination of some plant pathogens, *e.g.,* TMV, demands temperatures considerably higher than approximately 60 °C. Since the reduction of enterococci at 70 °C is highly efficient and fast (10E4 reduction in < 5 minutes (Lau et al. 2020), enterococci cannot be used as indicator organisms for the inactivation of heat-resistant plant pathogens. Thus, for those highly heat-resistant organisms it would be worthwhile to consider using the organism themselves as indicators, if possible.

2.2.3 Tests showing that the content of infective eggs from the indicator organisms *Ascaris suum* has been reduced to zero

Of the three validation organisms, Ascaris eggs (*Ascaris suum, A. Lumbricoides*) are considered the most robust. Their resilience to temperature, pH and moisture has recently attracted the attention of several research groups. These three parameters compound the rate of inactivation. Low temperature regime (7-13 °C) maintained the viability of *Ascaris suum* eggs for a long time (Berggren et al., 2004). In contrast, at a temperature of 70 °C and 80 °C, 100% inactivation was found after 125 min of exposure. Maya et al. (2012) stated that exposure of *Ascaris suum* eggs for 120 to 180 min to a combination of 78 °C, 74 °C and 68 °C with a dryness of 5%, 10% and 20%, respectively, resulted in 100% inactivation. 100 % inactivation could be achieved through elevated alkaline pH conditions (pH 12.7) combined with 20% dryness; however, after an exposure time of several month (8-9 months). The course of inactivation was dependent on the combination of pH and dryness and showed to be slower when the eggs were subjected to slightly lower pH (12.1) and higher moisture content conditions (10% dryness) (Maya et al., 2012). The compounding effect of elevated temperature and pH conditions on the inactivation rate of Ascaris eggs was also shown by Senecal et al. (2020). In their study, egg viability was lost four times quicker when the pH rose from pH 7.2 to pH 12.5 and temperature was kept at

35 °C. Matrix conditions seem to be important when determining the threshold temperatures for inactivation of Ascaris eggs.
Investigations have shown that low numbers of Ascaris eggs in biowaste were killed after composting (Déportes et al., 1998; Schwartzbrod et al., 1986). Trials with inoculation of biowaste with Ascaris eggs have revealed killing of eggs after 2-3 days at high temperatures (Christensen et al. (2001) and Strauch 1983 therein) but at lower temperatures (below 40 °C) the eggs were able to survive for several weeks. On the contrary, Harroff et al. (2019) found rapid inactivation (2 d) already at mesophilic temperature conditions (38-45 °C) under both aerobic and anaerobic conditions.

Apart from the previously named concerns regarding choice of human pathogens in presumably low load matrixes there are confounding parameters that remain to be identified. Feedstock may be one of these. Feedstocks displaying a rapid rise to high temperatures display a quicker inactivation of Ascaris eggs (Manga et al., 2016).

2.2.4 Final conclusion of the selected validation methodologies

In summary, none of the three validated organisms comply to the focus of the report, namely hygienisation of anaerobically or aerobically treated feedstock with respect to plant pathogenic and pest organisms (Table 11).

Table 11. Summary of the compliance of the validated organisms

Criteria	***Salmonella* Senftenberg**	***Enterococcus faecalis***	***Ascaris suum* eggs**
Useful for all type of feedstocks	Yes Presumably not present in high numbers Inoculation needed	Yes	Yes Presumably not present in high numbers Inoculation needed
Present whenever a plant pathogenic or pest organism is present	No	Environmental enterococci may be abundant; questionable if E. faecalis is present	No

Criteria	*Salmonella* Senftenberg	*Enterococcus faecalis*	*Ascaris suum* eggs
Longer survival time than the hardiest plant pathogenic or pest organism	No	No[1]	No [1,2]
Test method easily performed	Yes [3]	Yes	No[4]
Density of the indicator related to the presence of the potential plant pathogenic or pest organism	No	No	No

[1]TMV is more resistant [2]Conflicting information regarding inactivation temperature during anaerobic and aerobic degradation [3]Enumeration of viable counts by colony forming units excludes concepts of viable but non culturable or persister cells [4]Eggs may not disperse evenly in non-viscous matrix.

***Salmonella* Senftenberg as a validation organism:** Survival of many crucial pathogens is likely given the fact that the cardinal maximum temperature for *Salmonella* Senftenberg (775W, H2S-negative) is much lower than the ones for the hardiest pathogens (*e.g., Synchytrium endobioticum*, TobamoVirus). 5Log10 inactivation analysis are not common for inactivation studies with plant pathogenic organisms. Therefore, such comparison cannot be performed.

***Enterococcus faecalis* as a validation organism**: Survival of many crucial plant pathogens is likely since the reduction of enterococci at 70 °C is highly efficient and fast (10E4 reduction in < 5 minutes (Lau et al. 2020), but does not apply to the inactivation of heat-resistant plant pathogens (e.g., *Synchytrium endobioticum*, ToMoVirus). 5Log10 inactivation analysis are not common for inactivation studies with plant pathogenic organisms, since they do not have the same basis for validation. Therefore, such comparison cannot be performed.

Eggs of *Ascaris suum* as validation organism: Survival of many crucial plant pathogens is likely as inactivation conditions for eggs of *Ascaris suum* (temperature 70-80 °C; 125 min) fall below the ones of the hardiest plant pathogens (e.g., *Synchytrium endobioticum*, ToMoVirus).

Alternative indicator organisms: given the broad spectrum of pathogens potentially present in the feedstock and their broad range of environmental conditions facilitating inactivation, as well as the broad spectrum of technologies used for aerobic and anaerobic decomposition, it is unlikely to pinpoint one single organism useful for all different situations. Instead, process surveillance using a technological approach would be useful (see chapter 3).

2.3 Assessment of spread and establishment of harmful alien organisms from composting and biogas facilities

This chapter identifies harmful alien organisms that can pose highly negative consequences if spread to a new area. These are pests that both a) possibly are being associated with the pathway at origin, and b) are known from the literature to pose serious damage to the natural flora, biodiversity or crop production, or cause other serious problems to the farm, and/or c) have restricted occurrence in Norway.
The identified pests are listed in Table 13. Characterizations of the possible consequences of their spread are also given in the table. Such consequences could be reduced crop yield or quality, restricted future use of the land, extra costs due to control measures, restricted use of machinery or cooperation with other farms, etc. With a few exceptions, there is no reason to assume that harmful alien organisms can establish themselves in new areas if they are spread from composting and biogas facilities. It is only in those cases where a harmful alien organism has access to host plants or a favourable natural environment (for example, fertile soil in a sunny location for Japanese knotweed) and is not present or occurs at low levels in the receiving land area, that consequences of spread and establishment of these serious harmful alien organisms would be highly negative. Therefore, only organisms with restricted occurrence in Norway are included in Table 13. Restricted occurrence could be due to strict regulation of the organism, typically quarantine pests, whose further spread within Norway is prohibited or organisms that are reintroduced to Norway. It is important to keep in mind that all harmful alien organisms are detrimental to plants, biodiversity, nature, or to the quality of plant products, and that spread of all harmful alien organism are unwanted, also those not considered to be the most serious. Spread could cause increased prevalence of the organism, for example, escalating the establishment of invasive plant species, which is unfortunate in itself and might lead to an extended use of herbicides. Spread could also contribute to a greater genetic variation in the pest population.

2.3.1 Harmful alien organisms that may result in highly negative consequences if they are spread from composting and biogas facilities.

Harmful alien organisms can be dispersed from composting and biogas facilities
(i) during the process at the facilities (pre- and post-process storage, leakage, wind, aerosols, animal vectors, tools and machines, process handling as well as cross contamination) and/or
(ii) by the final product after it has left the facility, when used as soil improver, fertilizer or growing medium constituent.

Literature is very incomprehensive with respect to transmission routes related to the facility. No literature could be found with respect to pre-and post-process storage, leakage, animal vectors, tools and machines as well as cross contamination. Wind and aerosol have received more attention, but not mainly for plant pathogenic organisms rather with respect to adverse effects on occupational environment and public health. These findings can be paralleled to microbial plant pathogens. Activities related to movement of the feedstock (shredding, mixing, turning, screening) increased microbial structures in the aerosols (mainly bacterial cells, and to a minor extent bacterial and fungal spores) (Bru-Adan et al., 2009; Di Filippo et al., 2020; Fischer et al., 2008). Furthermore, wind displays a pathway for microbial structures, but also infected plant material and hazardous plant parts to the environment. In general, contained storage and processes mitigate potential dispersal from composting and biogas facilities. In this context it is worthwhile to highlight the risk for recontamination during post-process storage

In comparison to process related routes of transmission, the impact of dispersal by means of the final product is much stronger as spread volumes are substantially larger. In this context process temperature is decisive. In general, mesophilic process conditions do not counteract the majority of the portrayed target organisms. But also, thermophilic conditions allow heat resistant organisms and structures to survive. Table 12 lists hazardous alien organisms that can spread from compost and biogas facilities, their point of entry as well as risks for spreading.

Tabell 12. Selected hazardous alien organisms that can spread from compost and biogas facilities. ● represent feedstocks that might include the organism under certain situations. (●) represent feedstocks that we are unsure if the organism might be included or not. T estimated with a high uncertainty

Organism	Point of entry	Source of waste						
		Park and garden	Garden centers[1]	Kitchen[2] and restaurant[3]	Food/feed industry	Manure	Bulking material[4]	Husk cleaning debris[5]
Nematodes								
G. rostochiensis	Potato	●	(●)	●	●			
G. pallida	Potato	●	(●)	●	●			
Meloidogyne chitwoodi	Carrot, potato	●	(●)	●	●			
M. fallax	Carrot, potato, onion	●	(●)	●	●			
M. mali (EPPO A2 list)	Soil, roots	●	(●)					
B. xylophilus	Wood						●	

Organism	Point of entry	Source of waste						
Protozoa								
P. brassicae	Cruciferous plants, contaminated soil	●	●	●	●	●		
Fungi								
Synchytrium endobioticum	Potato peel and pulp	●	●	●	●	●		
Olpidium brassicae	Cucumber, melon, red squash, lettuce, tomato, ornamental flowers, *Chenopodium*, red clover, contaminated soil	●	●	●	●			
Fungal like organisms								

Organism	Point of entry	Source of waste						
P. ramorum	Infected plant material from nurseries, garden centers, parks and gardens	●	●					
Bacteria								
Clavibacter michiganensis subsp. *sepedonicus*	Potato (tuber and vegetative plant parts)	●	●	●	●			

[1] Wasted plants from garden centers; [2] Household kitchen waste; [3] Food waste from catering and restaurants; [4]Bulking material other then park and garden waste (e.g. shredded wood pallets);[5]Husks and seeds from contracted grain and seed husk cleaners

2.3.2 Conclusions on the spread and establishment of harmful alien organisms

Spread and establishment of harmful alien organisms from feedstock that only has been treated at mesophilic temperatures is likely with a low uncertainty.
Spread and establishment of alien organisms from digestates subjected to a pre- or post-process high temperature-high pressure hygienisation step (minimum temperature: 133 °C, pressure: 3 bar, exposure time: 20 min) is unlikely with a low uncertainty.

Nematodes: The spread of PWN *Bursaphelenchus xylophilus* from composting facilities is unlikely with a low uncertainty due to the absence of vector insects in compost. PCN, *G. rostochiensis* and *G. pallida* are moderately likely to spread with compost and establish after windrow composting where the temperature of the windrow is at least 55 °C for four weeks. This statement has a high uncertainty due to the lack of information on the prevalence of these pests in compost and the restricted number of hosts of the pests. For *B. xylophilus*, *G. rostochiensis* and *G. pallida,* a treatment at 70 °C for 60 minutes makes spread with compost and establishment unlikely with a low uncertainty. The root-knot nematodes *Meloidogyne* spp. are likely to spread with compost and establish, because of the high number of hosts of the pest. This statement has a high uncertainty due to the lack of information on their prevalence in compost. Treatment at 70 °C for 60 minutes makes the spread with compost and establishment unlikely with a high uncertainty.

Protozoa: *P. brassicae* is able to survive well throughout adverse conditions, and therefore it could potentially enter and also survive composting if the substrate contains contaminated debris of Cruciferous plants. It is also likely to spread afterwards, since it is naturally disseminated via water and soil. It can survive for at least 17 years in soil (Wallenhammar, 1996). The overall conclusion for spread and establishment for protozoa will be unlikely if care is taken to avoid the introduction of contaminated material, with a low level of uncertainty.

Fungi: The winter sporangia of *S. endobioticum* will likely survive the conditions described in ToR 1. They are present inside warty, cauliflower-like protuberances of infected potato tubers and stolons, which, depending on the particle size and conditions, partly can exit the treatment processes unscathed, leaving the resting sporangia in a dormant state. Waste coming from the potato industry could represent the highest risk of contamination with this pathogen, and should thus preferably be treated separated from composting facilities. However, also waste from e.g. private households represents a certain risk, and thus there is a certain risk of spread from such sources. Therefore, the overall conclusion on spread and

establishment for *S. endobioticum* is considered to be likely with a moderate uncertainty. *O. brassicae* and related *Olpidium* species produce resting spores that can survive for decades in soil (Maccarone, 2013), so, if some spores did survive composting (see Section 2.1), they would likely spread with the finished compost to new areas. The level of uncertainty is medium. *Fusarium* species are disseminated through soil; thus, movement of infested soil is a potential pathway for its introduction to new areas. It is also carried by splashes of water to other plants. However, as seen in Section 2.1, propagules of this pathogen can be reduced in the organic material if composting and heat treatment are carried out according to the operating conditions specified in ToR 1. Therefore, the risk of dissemination and establishment of *Fusarium* species from treated material is considered low with a high degree of certainty. For *S. sclerotiorum*, the fate of the pathogen has varied in different studies e.g. those by Downer et al., 2008, Bollen et al., 1989. The most important factor for obtaining consistent and effective eradication is the presence of adequate moisture levels. If the treatment (AD or composting) is conducted in moist conditions, the pathogen levels should be sufficiently low to not pose a risk for dissemination and establishment elsewhere, with high degree of certainty.

Fungal-like organisms: Generally, treatment at 70 °C for 60 min should suffice for killing off *Phytophthora* species. It is a higher temperature than those measured in reports on *Phytophthora* in compost trail. However, when using dry heat at 55 °C, 1 hour is sufficient to kill *Phytophthora* propagules (Swain et al. (2006)). There is some level of uncertainty of the critical time-temperature required for eradication of *Phytophthora* species, due to the erratic way that they behave in composts, even in the same study (Downer et al., 2008); in which it was impossible to make a goodness-of-fit analysis for survival of *P. cinnamomi* in fresh and aged composts for specific periods of time at certain temperatures. Swain et al. (2006) found that *P. ramorum* was non-detectable after composting for 2 weeks at 55 °C. *P. ramorum* can contaminate compost piles while they are maturing and survive there. A carefully designed study of different kinds of composts (windrows as well as forced air static piles) with different levels of maturity demonstrated that sporangia or zoospores were able to survive in ripening compost (i.e. after the thermophilic phase) if they, for example, had spread from an adjacent compost pile with fresh green waste (Swain & Garbelotto, 2015). It is common practice to allow composts to mature for several weeks after the composting process is completed. *P. ramorum,* which was studied by these authors, would pose a threat to native Norwegian forest trees if it were to spread from a composting/biogas facility, for example with run-off water into adjacent water bodies, if these are in the close vicinity of native woods. We consider it unlikely with medium level of certainty that *Phytophthora* species may spread after AD/composting processes.

Bacteria: *Clavibacter michiganensis* subspecies (*Cms* and *Cmm)* and *Ralstonia solanacearum* are moderately likely to survive composting at 55 °C for four weeks, although this depends on the conditions present during the composting, such as moisture content, and thus their potential survival comes with a high degree of uncertainty. The primary source of infection for both *C. michiganensis* subspecies is seed (potato tubers for *Cms* and tomato seeds for *Cmm*). Tomato seeds survive better than potato tubers after composting or biogas digestion, but on the other hand, *Cms* poses a greater threat in the cool climate of Norway than *Cmm*. *R. solanacearum* could spread with surface water from the composting/biogas facility to wild weeds that are known to serve as alternate hosts (Wenneker et al., 1999). For their successful establishment after dissemination, they would need to find suitable host plants. Since they all three thrive best in their native or closely related hosts. The level of uncertainty is medium.

Plants: Information is limited on the fate of Japanese knotweed and giant hogweed after composting, anaerobic digestion and heat treatment at 70 °C. What is well-established is that both plant species continue to spread to new areas and successfully establish themselves, so the likelihood of this continuing is high. These two are also often considered as "hagerømlinger" in Norway (Aschjem and Finstad Brevik, 2016). Giant hogweed spreads exclusively through seeds. A single plant produces an enormous number of seeds, and most of them land on the ground next to the plant. Seeds are disseminated either by movement of contaminated soil or water. Japanese knotweed can regenerate new plants from both stem fragments (if they land in moist, nutrient rich soil) or tiny rhizome fragments. Plant parts could disperse on the way to the composting facility/waste deposit site if they are not well-contained. It spreads effectively through contaminated soil and water. Its natural way of spreading to new sites is by rhizome fragments carried along waterways. Private persons, whose gardens are infested with Japanese knotweed may inadvertently deposit rhizome and stem fragments in the municipal composting facility, which later will survive and result in the establishment of plants at new sites. Likewise, seeds of Giant hogweed can be buried in soil that is shifted, with or without plant waste, which, if they end up in compost piles, possibly could spread from there by water leaching out, even thou this is most a theoretical aspect. These statements have medium to high uncertainty. However, it is due to the small amount of tiny rhizome fragments that will give Japanese knotweed it's higher potential to survive the compost and biogas processes (see: table 9) and therefore are considered in table 13. The probability of establishment is high if they manage to enter the composting facility and survive the process.

Viruses: The spread of viruses from composting facilities is generally unlikely with low uncertainty due to i) inability or avoidance? of virus vectors to take up and thus transmit viruses from the compost ii) breakdown over time of free virus particles (even heat-resistant

viruses such as TMV and TRV) and the assumed lower ability of the host plants to take up viruses from amended compost in the field. However, viruses that are vectored by fungi or fungus-like organisms such as *Spongospora* (Potato Mop-top virus)*, Polymyxa* (Barley Yellow Mosaic virus, Beet Necrotic Yellow Vein virus) and *Olpidium* (Tobacco Necrotic virus) may pose a risk of spread and establishment in crops or weed species in the field if these vectors are not inactivated during composting. This later statement has a high degree of uncertainty because of lack of literature on the subject.

Table 13. Plant pests and alien organisms that have a potential to survive composting and/or anaerobic digestion and/or also may cause highly negative consequences if spread to new land areas afterwards. Only harmful alien organism with restricted occurrence in Norway are included, and they have all been identified to possibly be associated with the pathway at origin.

Organism	Negative consequences if spread to a new area
Reynoutria japonica	*R. japonica* is a fast-spreading plant which is very competitive. No effective herbicides are available, and the cost of control is high. If this plant appears in connection with riparian areas, it establishes well and will effectively spread over large distances, since detached plant parts can be carried with water streams. Above-ground plant parts of *R. japonica* are unlikely to survive during digestion. However, the rhizomes are considered impossible to digest, unless a special pre-treatment step, designed for wood and woody materials, is included.
Sclerotium cepivorum	*S. cepivorum* is the causal agent of the disease commonly known as Allium root rot. Allium root rot can be serious pathogen since it can result in large crop losses. The sclerotia can survive in the soils for decades.
Synchytrium endobioticum	The potato wart fungus, *S. endobioticum,* is under Phytosanitary regulation. The potato wart fungus is a serious pathogen that reduces the yield and quality of the potato harvest.
Globodera rostochiensis, G. pallida	The potato cyst nematodes (PCNs) are under Phytosanitary regulation. The PCNs represent a serious problem, as they can survive for up to 32 years in soil following an infestation. PCN infestation reduces potato yield and quality.

Meloidogyne chitwoodi, M. fallax	These species of root-knot nematodes are under Phytosanitary regulation. They are a serious problem because of the very broad host range. The infestation causes crop reductions in many crops, and will due to the strong regulation stop the growing of host plants for considerable time.

3 Risk reduction options and their effectiveness and feasibility

3.1 Identify relevant risk reduction options and evaluate their effectiveness and feasibility.

3.1.1 Alternative indicator organisms other than those mentioned under 2.2

As mentioned in 2.2, there is no such "magic" indicator organism that mimics the response of all undesired organisms during anaerobic and aerobic degradation. Three organisms have been considered as alternative indicator organisms for direct process validation (EPPO, 2008), namely tobamovirus (TMV), *Plasmodiophora brassicae* and tomato seeds. Tobamovirus and resting spores of *P. brassicae* display considerable resistance to high temperature. According to phytosanitary procedures described by EPPO, none of the three organisms should be detectable at infective levels or germinate (tomato seeds) post process. All three procedures involve spiking of the feedstock, with either TMV or *P. brassicae* infected material according to Bruns et al. (1994) and Idelmann et al. (1998) or amendment of tomato seeds in sealed non-decomposable gauze sachets (EPPO, 2008).
P. brassicae has been commonly used as an indicator organism during AD (Westerman and Gerowitt, 2013). It has also been suggested as a phytosanitary indicator organism for compost, as reviewed by Witchuk et al. (2011). However, it was deemed unsuitable as an indicator organism for compost, due to its inconsistent survival rate (Noble, 2011).

3.1.2 Other risk reduction options (RROs)

3.1.2.1 Thermal conditions

An inherent temperature cycle occurs during aerobic decomposition. Temperature rises to 45 °C and to 65-70 °C during the first mesophilic and thermophilic phases, respectively. Given that all other environmental factors play a minor role during the mesophilic phase, most organisms listed in Table 7 will not be affected by peak temperature during the first mesophilic composting phase. This also means, that a composting purely based on mesophilic conditions is not a sufficient risk-reducing measure. At the same time, thermophilic conditions during composting per se will not be sufficient to reduce the risk of the hardiest hazardous alien organisms, such as tobamoviruses, *Synchytrium endobioticum, Fusarium oxysporum, Meloidogyne incognita* and *M. fallax* (due to the expected survival of

eggs in egg sacs), as well as bacterial spores. However, the compost pile is a medium with multiple simultaneous stresses, e.g., alkaline pH and high temperature, which affects survival, reproductive capacity and virulence.
To account for survival of the hardiest pests and pathogens, pre- and post-process treatments may be added on the different modes of organic matter transformation, especially with regard to AD. These have an important influence on microbial community composition of the final product and the potential presence of undesired organisms. Common pre-process treatments aim at feedstock disintegration and use physical (thermal: low or high temperature treatment, microwave treatment; mechanical; electrical), chemical (acid hydrolysis, alkaline hydrolysis, thermal-chemical wet oxidation; activated wet oxidation) and biological/biochemical techniques (addition of microorganisms or enzymes). Table 14 displays the impact of some treatments on the survival of selected animal and human pathogens. In contrast to composting, organic matter retrieved from AD may be subjected to a thermal post-process treatment at either low (minimum temperature: 70 °C; exposure time:1 h) or high temperature and high pressure (minimum temperature: 133 °C, pressure: 3 bar; exposure time: 20 min), respectively. No information was available to which extent these processes are used in Norwegian facilities.

Table 14. Impact of thermal and chemical methods on the survival of selected animal and human pathogens (according to Franke-Whittle and Insam (2013); modified). Mentioned organisms and structures serve as examples for non-spore forming, facultative anaerobic bacteria of the Enterobacteriaceae (*Escherichia coli, E. coli; Salmonella*), aerobe spore forming bacteria (*Bacillus anthracis*)*, a*naerobic spore forming bacteria, that may be toxigenic (*Clostridium)*, non-spore forming, aerobe coccobacilli (*Brucella abortus*) and heat resistant prions (causing bovine spongiform encephalitis, BSE, also called mad cow disease). *(*++: absolute inactivation; +: inactivation to large extent; -: survival; ?: unknown; ?-: unknown, but probable survival; ?+: unknown, but inactivation most likely).

Pathogens	**Pasteurization (P), i.e. 70 °C for 1 hour**	**Mesophilic biogas fermentation (M)**	**Thermophilic biogas fermentation**	**P+M**	**Composting**	**Alcalinic hydrolysis**
E. coli	++	+	+	?+	+	?+
Salmonella	++	+	++	?+	++	?+
Clostridium	-	-	-	?-	-	?+
Brucella abortis	++	?	?+	?+	?	?+

Pathogens	Pasteurization (P), i.e. 70 °C for 1 hour	Mesophilic biogas fermentation (M)	Thermophilic biogas fermentation	P+M	Composting	Alcalinic hydrolysis
Bacillus anthracis	-	-	-	?-	-	?+
BSE	-	-	-	?-	-	++

3.1.2.2 Barriers and containment

To avoid spread and cross contamination of harmful alien organisms within the composting and biogas facilities it is important to have established "clean" and "dirty" zones with clear barriers. Awareness of cross contamination via machinery as a vector of transmission is needed.

Transmission/dispersal may also occur before the AD or composting takes place. As an example, *P. ramorum* may be transmitted through leakage to nearby ditches for further spread downstream. A possible solution would be a concrete ground during the processes or closed compartments/facilities. As mentioned previously, Swain & Garbelotto (2015) demonstrated that composts that are ripening at the end of the process, are vulnerable to contamination by dispersal propagules (zoospores and sporangia) of *P. ramorum* and that this pathogen can survive there. They suggest that fresh green garden waste should not be mixed with finished compost and there should not be any fresh heaps nearby. The area near the composting/biogas facility should be monitored for symptoms on possible host plants, since leaves of foliar hosts are extremely infectious (Swain & Garbelotto, 2015).

Seeds and insects may be dispersal by wind extra barriers and/or containing should be established to avoid contamination of harmful alien organisms in the close areas to the facilities.

Strict control of animals (insects, rodents, birds) should be managed to avoid cross contamination and spread of harmful alien organism within the facilities and its close surroundings.

3.1.2.3 Material entering

Organisms of importance for dispersal are presented in Table 14. Material vectoring these organisms deserve special attention in feedstocks, especially:

1. Potato residues
2. Onion residues
3. Japanese knotweed

Garden and park waste may pose plant health risks if added to windrow composting systems. As an example, the nematodes *Globodera rostochiensis*, *G. pallida*, *Meloidogyne chitwoodi* and *M. fallax*. Compost facilities need to consider pre-treatment (preferably high temperature / high pressure treatment) of these risk materials as an important risk reduction option. This is not necessary for horse and chicken dung.

3.1.2.4 Material leaving

Heavily contaminated material should be prevented from entering any of the assessed processes.

Considering the organisms that may pose a risk, potato and onion would be two of the crops at highest risk of being exposed to hazardous organisms after compost amendment.

Therefore, use of compost should be restricted on fields intended for potato or onion cultivation.

Compost-containing material from gardens and parks and shredded pallets would pose no plant health risks if it has been appropriately pre-treated with heat, or if the compost has been treated during maturation. Without pre- or post-treatments, such material might pose plant health risks if used in agriculture and horticulture.

3.2 Conclusion to risk reduction options and their feasibility

All risk reduction options under "Barriers and containment" has a high efficacy with a low uncertainty and assessed as medium feasible with a high uncertainty.

Heat treatment of waste has high efficacy with high uncertainty, and assessed as highly feasible for many viruses, bacteria, fungi, insects, slugs, plants and some nematodes. The efficacy is low to medium for *Synchytrium endobioticum*, *Plasmodiophora brassicae*, *Globodera* spp. and *Meloidogyne* spp. due to the thermo-tolerance of these pests. The feasibility of heat treatment is low to medium with a high degree of uncertainty for the heat-tolerant pests (Table 15).

Table 15. Selected hazardous alien organisms that can spread from compost and biogas facilities, points of entry and preventive control measures

Organism	Point of entry	Preventive measure
Nematodes		
Globodera rostochiensis	Potato residues from garden and food waste as well as industry	Pre- / post treatment 70 ° C for 1 h by wet heat
G. pallida	Potato residues from garden and food waste as well as industry	Pre- / post treatment 70 ° C for 1 h by wet heat
Meloidogyne chitwoodi	Potato, carrot and onion residues from garden and food waste as well as industry	Pre- / post treatment 74 ° C for 4 h, 80 ° C for 2 h or 90 ° C for 1 h by wet heat

M. fallax	Potato, carrot and onion residues from garden and food waste as well as industry	Pre- / post treatment 74 ° C for 4 h, 80 ° C for 2 h or 90 ° C for 1 h by wet heat
M. mali	Soil and roots	Pre- / post treatment 74 ° C for 4 h, 80 ° C for 2 h or 90 ° C for 1 h by wet heat
Fungi		
Synchytrium endobioticum	Potato residues from both gardens and food waste.	Removal of infected material
Protozoa		
Plasmodiophora brassicae	Garden and food waste, as well as industrial waste (especially from cruciferous plants)	Removal of infected material

4 Uncertainties

Limited information could be acquired from Avfall Norge with respect to facility design and size, used processes, feedstock components, management and process length as well as pre- or post-process treatments. Given the broad range of practical processes and variations in process lengths, this constitutes an important uncertainty with regard to the application of conclusions drawn in the present report.

The large variability in temperatures in open windrow composting is an important component of uncertainty. Temperatures may be difficult to monitor due to the large volumes of material involved. In particular, the bottom of the windrow is cooler, due to its contact with the ground or underlying support. This position is also difficult to monitor. This also relates to the outer surfaces of the windrow. The distribution of temperature through the windrow is also affected by the number of turnings and the precision of this, which adds to the uncertainty. ToR 1 called for the assessment of the effect of maintaining 55 °C for a period of 4 weeks in a windrow and/or 1 week in compost that is turned four times over 4 weeks. This has been impossible to evaluate, since these specific conditions are not reported for each pathogen in the literature. Instead, the composting process used in studies of pathogens usually reports 55 °C (or higher) for a few days when the compost is fresh, followed by a significant drop in temperature. Older or mature compost was not as efficient as fresh compost in inactivating plant pathogens. In addition, the type of material processed, and its variation between facilities and over the season will influence the composting process and the risk of inadvertently introducing pathogens that can survive. Household wastes and plant wastes from gardens and parks may pose plant health risks due to the possible occurrence of quarantine pests. Garden waste may be the major component of the process or it can be added as a complement to the composting of other materials. There is limited information on temperature profiles of continuous composting systems, such as beds, drums and silos. The information is also limited regarding the efficacy of various aerobic and anaerobic processes in the sanitation of plant pests, and the degree to which plant pathogens escape in the effluent from such processes. The degree to which pre-treatment or post-treatments are applied to plant waste before and after the main process, and their efficacy on resistant stages of plant pathogens is unknown. Still, only little information is available on the effect of temperature and exposure time on the most decisive factors, *i.e.* the infection potential and the reproductive rate of pest organisms. A study of the germination of seeds of *E. crus-galli* after AD showed that the origin of the seed lot could influence the time-temperature requirement (Zhou et al., 2020). Confounding results can also be obtained due to the absence of reliable pathogenicity tests, as in the case of *Synchytrium endobioticum*, where the latest recommendation is to microscopically examine samples, rather than conduct pathogenicity tests/bioassays (Schleusner et al., 2019). The

latter are often seen as the ultimate test of pathogen survival and infectiousness, and a straight-forward, practical answer to the risk to end-users (Noble & Roberts, 2003). Bio-PCR methods are also being used by researchers, but their practical significance in terms of evaluating the biological hazard of the organic matter resulting from composting or AD needs further studies.

Full-scale AD units can operate continuously or in batches. Mixed reactors take in new substrate as old digestate leaves, but due to the mixing, substrate is retained in the reactor for a varying period of time, and even if the average time spent in a reactor is 22 days, some substrate may only spend 1 day in the reactor. For the continuous type of AD reactor, a small part of the digestate may not spend sufficient time in the digestor to kill off all pathogens (Henry et al., 2013).

ToR 1 calls for an evaluation of pathogen kill-off as a function of exposure time and temperature. The present report demonstrates with several examples that the situation is not so straightforward, for example regarding the moisture status of the substrate. High moisture levels will enable kill-off at lower temperatures, as was already demonstrated almost 100 years ago. High moisture conditions are considered important for the eradication of most if not all pathogens (Glynne, 1926). In addition, there are other factors that come into play, such as pH and ammonia levels, exemplified by the thermosensitivity of TMV at alkaline pH (Herrmann et al., 1994). Digestate from AD usually is quite alkaline (pH of approx. 8). Composting usually implies a pH of 5.5-8 (Bollen & Volker, 1996). The way in which factors other than temperature and time of exposure may contribute to sanitation is not clear (Seigner et al., 2010; Bollen & Volker, 1996). Because temperature and exposure time are the easiest parameters to monitor practically, and results from such an analysis could lead to practical recommendations and survey systems, several reviews have used the same approach (Wichuk et al., 2011; Noble & Roberts, 2004; Noble et al., 2009).

These additional environmental factors could in part explain the inconclusive data reported on some of the pathogens reviewed in this report. Different time periods and temperature regimes for eradication have been stated in the literature, and it is actually impossible to reach a general consensus. A higher temperature and exposure time than those experimentally verified can be the final recommendation for eradication, in order to ensure sufficient efficiency of the treatment, such as was done in the UK (PAS 100), where 65 °C for 7 days and 51 % mass moisture/mass would eradicate most pathogens. Interestingly, for several of the pathogens with conflicting results, there is ample literature on the disease-suppressive effects of compost (see reviews by St. Martin & Braithwaite, 2012; Raviv, 2007), for example, *Phytophthora* species (Labrie et al., 2001; Pitt et al., 1998; Rafferty et al., 2004; Garcia et al., 2004), *Fusarium* spp. and several plant parasitic nematodes (Toyota, , *S.*

sclerotiorum (Garcia et al., 2004; Tao et al., 2014), *P. brassicae*, *R. solanacearum* (Mengesha et al., 2017; Mary & Mathew, 2016)*, C. m. sepedonicus* (Cherusová et al., 2016). This suggests that compost and perhaps also digestate has other beneficial components that can be very important to take into consideration. Composting of the digestate after AD has been proposed as a method of further sanitation (Ryckeboer et al., 2002; Bustamente et al., 2012).

There are pockets in compost piles where environment is anaerobic (Rijn & Termorshuizen, 2007). They found that a pathogen (*Polymyxa betae*) was eradicated in anaerobic conditions at a specific temp (40 °C) over a time period, which did not happen under similar aerobic conditions. They surmised that *P. brassicae*, which is taxonomically related to *P. betae* is similarly inhibited in anaerobic pockets in composts, i.e. that an anaerobic environment would also render this pathogen more sensitive to the treatment. The maceration of plant pieces into finer fragments is usually considered a good way to ensure eradication of pathogens, since the pathogens are no longer able to hide within the substrate. However, for pathogens that are difficult to inactivate, the effect can be the opposite, for example, winter sporangia of *Synchytrium* were released into the bioreactor during AD and increased in number, with longer exposure times of the potato warts in the wart compost to the stirred tank reactor (Schleusner et al., 2019).

There are other pathogens, which potentially pose a risk in Norway that are not covered in this report, due to limited original literature reports, but are mentioned in a literature review by Noble and Roberts (2004) and Noble et al., 2009, for example, PSTDv, which is heat resistant.

5 Conclusions (with answers to the terms of reference)

1. **Assess whether critical operating conditions which are often used in the sanitation stage of composting and biogas facilities is adequate in order to prevent the spreading of plant pests (including viable plant parts and seeds) and harmful alien organisms (hereinafter alien organisms).**
    a. **Composting in windrows (> 2.5m) or mattresses where the temperature of the windrow is at least 55 °C for four weeks and the windrow is turned at least three times during this period.**

The Panel concludes that these methods will not eradicate all potential harmful organisms during the process. For example, *S. endibioticum*, *Globodera* spp., *Melodigyne* spp. Our conclusion is that it is difficult to establish a minimal number of required turnings of a windrow or a mattress, because of the discrepancy in conditions of different facilities and in the composting processes.

    i. **Also assess a variation of this whereby sanitation is divided into four periods with a temperature of at least 55 °C for at least one week, but where there can be intervals between each of these periods during which temperature is not measured. The material must be turned between each of these four periods.**

The Panel concludes that there will be uncertainties in mitigating plant pests and alien organism risks if the composting process is divided into periods. The same uncertainties, with regard to variations in temperatures, will be relevant in this case, as well as the difficulty of correct monitoring the process variables.

    b. **Treatment at 70 °C for 60 minutes with a max particle size of 12 mm whereby this is achieved in a composting process or as a pre-treatment step before an anaerobic treatment process.**

The panel concludes that a pre-treatment at 70 °C for 60 min of material of a particle size of 12 mm will free the material from most quarantine pests, with the possible exception of *Meloidogyne* spp. and *Synchytrium endobioticum*, which would require temperatures higher than 70°C for several days. The decisive factors, i.e. infectivity and reproduction, still remain to be investigated for many quarantine pests.. Root knot nematodes could survive anaerobic digestion with thermophilic acetogenesis/methanogenesis.

2. If the treatment facility uses other sanitation methods than those listed in point one: Assess whether the following validation methodology is appropriate in order to ensure that the sanitation method being used is adequate in order to prevent the spread of alien organisms in compost and digestate:

a. 5log10 inactivation of *Salmonella* Senftenberg (775W, H_2S-negative)

The Panel concludes that the survival of many pathogens crucial for plants is likely as the cardinal maximum temperature for *Salmonella* Senftenberg (775W, H_2S negative) is much lower than the ones of the hardiest organisms.

b. 5log10 inactivation of *Enterococcus faecalis*

The Panel concludes that cardinal temperature lethal to *Enterococcus faecalis* do not apply to inactivation of heat-resistant plant pathogens.

c. tests showing that the content of infective eggs from the indicator organism *Ascaries suum* has been reduced to zero.

The Panel concludes that cardinal temperature for inactivation of eggs of *Ascaris suum* fall below the ones of the hardiest plant pathogens.

d. Assess whether alternative indicator organisms other than those mentioned in points 2a to 2c could better describe the probability of alien organisms not surviving.

The Panel could not identify one single, or set of, organism(s) that matches these requirements to serve as a universal indicator organism, based on the scientific literature retrieved.

Tobamoviruses, *Plasmodiophora brassicae* and tomato seeds have been considered as alternative indicator organisms for direct process validation. Tobamovirus and resting spores of *P. brassicae* display considerable resistance to high temperatures, but none of the three organisms should be detectable at infective levels or germinate (tomato seeds) post process. All three organisms involve spiking of the feedstock, with either TMV or *P. brassicae* infected material or amendment of tomato seeds in sealed non-decomposable gauze sachets.

3. Assess the probability that harmful alien organisms will spread further from composting and biogas facilities if the waste is treated in accordance with the requirements set out in points one or two.

The Panel concludes with that there is no reason to assume that harmful alien organisms generally can establish themselves in new areas if they are spread from composting and biogas facilities, unless host plants or favorable natural environments are present. Spread and establishment of harmful alien organisms is likely with a low uncertainty from feedstock that only has been exposed to mesophilic conditions. However, spread and establishment of alien organisms from digestates subjected to a pre- or post-process high temperature-high

pressure hygienisation step (minimum temperature: 133 °C, pressure: 3 bar, exposure time: 20 min) is unlikely with a low uncertainty.

4. Identify harmful alien organisms that may result in highly negative consequences if they are spread from composting and biogas facilities.

The Panel has selected plant pests and alien organisms that have a potential to survive composting and/or anaerobic digestion and/or also may cause highly negative consequences if spread to new land areas afterwards are presented.
In conclusion, *R. japonica*, *S. cepivorum*, *S. endobioticum*, *G. rostochiensis*, *G. pallida*, *M. chitwoodi* and *M. fallax* are identified as harmful alien organisms that may result in highly negative consequences if they are spread.

5. Identify relevant risk-reducing measures and evaluate their effectiveness and feasibility.

The Panel has listed several risk-reducing measures in Chapter 3.
To achieve eradication of the hardiest pests and pathogens, pre- and post-process treatments may be added on the different modes of organic matter transformation, especially with regard to AD. Common pre-process treatments aim at feedstock disintegration and use physical (thermal: low or high temperature treatment, microwave treatment; mechanical; electrical), chemical (acid hydrolysis, alkaline hydrolysis, thermal-chemical wet oxidation; activated wet oxidation) and biological/biochemical techniques (addition of microorganisms or enzymes).
Organic matter retrieved from AD may be subjected to a thermal post-process treatment at either low (minimum temperature: 70 °C; exposure time:1 h) or high temperature and high pressure (minimum temperature: 133 °C, pressure: 3 bar; exposure time: 20 min), respectively.

Heavily contaminated material should be avoided entering any of the assessed processes. Sensor surveillance of processes and parameters ensures process consistency.
Potato and onion are two of the crops at highest risk of being exposed to hazardous organisms after compost amendment. Therefore, use of compost should be restricted on fields intended for potato or onion cultivation.
Composted garden and park waste pose no plant health risks if appropriately pre-treated with heat. Without pre- or post-treatments, such material might pose plant health risks if used in agriculture and horticulture. The panel are aware of the limited feasibility of such measures.

The Panel refers to UK recommendations stating that conditions of 65 °C heat treatment for 7 days with a minimum of 51 % mass moisture/mass would eradicate most pathogens (PAS 100).

6 Data gaps

Several data gaps have been pinpointed and discussed under chapter 4.

Generally, there is a need for knowledge of how different organisms behave under different practical compost and biogas processes. If this information would be available, we would be able to more precise predict the outcome and lower the uncertainty.

There is need for knowledge of what the feedstocks carries for potential harmful alien organisms. No such information was accessible for the panel. Studies of the different feedstock components and what kind of harmful alien organism they include would greatly have made a difference in evaluating which alien organisms that can spread from compost and biogas facilities, their points of entry and as well as preventive control measures to evaluate.

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Appendix I

Ratings and descriptors

Ratings and descriptors are modified from Appendix E in: EFSA PLH Panel (EFSA Panel on Plant Health), 2015. Scientific Opinion on the risks to plant health posed by *Xylella fastidiosa* in the EU territory, with the identification and evaluation of risk reduction options. EFSA Journal 2015; 13(1):3989, 262 pp. doi:10.2903/j.efsa.2015.3989.

Table AI-1. Rating of probability of association with the pathway at origin

Rating	Descriptors
Unlikely	The likelihood of association would be low because the pest: • prevalence is zero or low; • does not feed on or attack the respective host plant(s) by the time of harvesting and/or grazing; • does not carry mature seeds by the time of harvesting and/or grazing; • escapes the harvester and/or grazing animal by active migration (winged insects);
Moderately likely	The likelihood of association is considered moderate because the pest: • prevalence is moderate; • feeds on or attack the respective host plant(s) by the time of harvesting and/or grazing, but the pest population size is currently moderate; • carries moderate amounts of mature seeds by the time of harvesting and/or grazing; • partly escapes the harvester and/or grazing animals by active migration (winged insects);
Likely	The likelihood of association would be high because the pest: • prevalence is high; • feeds on or attack the respective host plant(s) by the time of harvesting and/or grazing, and the pest population is at its peak; • carries large amounts of mature seeds by the time of harvesting and/or grazing; • does not escape the harvester and/or grazing animal by active migration (less mobile species of insects and mites or immobile and less mobile life stages of insects and mites);

Table AI-2. Rating of the probability of survival

Rating	Descriptors
Unlikely	The likelihood of survival is considered low because: • the pest is particularly sensitive to the exposing conditions; • the conditions are highly unfavourable compared to the tolerance of the pest; • the exposure time is very long compared to the tolerance of the pest;
Moderately likely	The likelihood of survival would be moderate because: • the pest is moderately sensitive to the exposing conditions; • the conditions are moderately unfavourable compared to the tolerance of the pest; • the exposure time is moderately long compared to the tolerance of the pest;
Likely	The likelihood of survival would be high because: • the pest is insensitive to the exposing conditions; • the conditions are not unfavourable compared to the tolerance of the pest; • the exposure time is short compared to the tolerance of the pest;

Table AI-3. Rating of the probability of establishment

Rating	Descriptors
Unlikely	The likelihood of establishment would be low because: • of the limited availability of host plants; • the unsuitable environmental conditions over the majority of the risk assessment area; • the occurrence of other obstacles preventing establishment;
Moderately likely	The likelihood of establishment would be moderate because: • hosts plants are abundant in some areas of the risk assessment area; • environmental conditions are suitable in some areas of the risk assessment area; • only few other obstacles to establishment occur;
Likely	The likelihood of establishment would be high because: • hosts plants are widely distributed in the risk assessment area; • environmental conditions are suitable in the risk assessment area; • no obstacles to establishment occur;

Table AI-4. Rating of the probability of spread

Rating	Descriptors
Unlikely	The likelihood of spread would be low because: • association with the pathway at origin is unlikely; • survival through the whole pathway is unlikely; • establishment on the receiving agricultural area is unlikely;
Moderately likely	The likelihood of spread would be moderate because: • association with the pathway at origin is moderately likely; • survival through the whole pathway is moderately likely; • establishment on the receiving agricultural area is moderately likely;
Likely	The likelihood of spread would be high because: • association with the pathway at origin is likely; • survival through the whole pathway is likely; • establishment on the receiving agricultural area is likely;

Table AI-5. Ratings used for describing the level of uncertainty

Rating	Descriptors
Low	No or little information or no or few data are missing, incomplete, inconsistent or conflicting. No subjective judgement is introduced. No unpublished data are used.
Medium	Some information is missing or some data are missing, incomplete, inconsistent or conflicting. Subjective judgement is introduced with supporting evidence. Unpublished data are sometimes used.
High	Most information is missing or most data are missing, incomplete, inconsistent or conflicting. Subjective judgement may be introduced without supporting evidence. Unpublished data are frequently used.

Appendix II

Literature search output.

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#1	(("Thermal inactivation") OR ("Heat treatment")) AND (("Reynoutria japonica") OR ("Japanese knotweed") OR ("Fallopia japonica")OR ("Polygonum cuspidatum"))	WoS	4	0	4	4	0	0	0
#2	((compost*) OR ("Heat treatment")) AND (("Reynoutria japonica") OR ("Japanese knotweed") OR ("Fallopia japonica") OR ("Polygonum cuspidatum"))	WoS	18	0	18	14	4	1	3
#3	(("anaerobic digestion") OR ("Heat treatment")) AND (("Reynoutria japonica") OR ("Japanese knotweed") OR ("Fallopia japonica") OR ("Polygonum cuspidatum"))	WoS	7	0	7	4	3	0	3
#4	(("Thermal inactivation") OR ("Heat treatment")) AND (("Echinochloa crus-galli") OR ("Cockspur grass"))	WoS	8	0	8	2	6	0	6

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#5	((compost*) OR ("Heat treatment")) AND (("Echinochloa crus-galli") OR ("Cockspur grass"))	WoS	49	0	49	33	16	0	16
#6	(("anaerobic digestion") OR ("Heat treatment")) AND (("Echinochloa crus-galli") OR ("Cockspur grass"))	WoS	18	0	18	12	6	0	6
#7	(("Thermal inactivation") OR ("Heat treatment")) AND (("Heracleum sphondylium") OR (hogweed) OR ("Heracleum mantegazzianum") OR ("giant hogweed") OR ("Heracleum persicum"))	WoS	2	0	2	2	0	0	0
#8	(compost*) AND (("Heracleum sphondylium") OR (hogweed) OR ("Heracleum mantegazzianum") OR ("giant hogweed") OR ("Heracleum persicum"))	WoS	4	0	4	2	2	0	2
#9	("anaerobic digestion") AND (("Heracleum sphondylium") OR (hogweed) OR ("Heracleum mantegazzianum") OR ("giant hogweed") OR ("Heracleum persicum"))	WoS	18	0	18	0	18	0	18

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#10	(("Thermal inactivation") OR ("Heat treatment")) AND (("Ralstonia solanacearum") OR ("Burkholderia solanacearum") OR ("Bacillus solanacearum") OR ("Pseudomonas solanacearum") OR ("Pseudomonas batatae") OR ("Pseudomonas ricini"))	WoS	36	0	36	31	5	0	5
#11	(compost*) AND (("Ralstonia solanacearum") OR ("Burkholderia solanacearum") OR ("Bacillus solanacearum") OR ("Pseudomonas solanacearum") OR ("Pseudomonas batatae") OR ("Pseudomonas ricini"))	WoS	100	0	100	89	11	0	11
#12	("anaerobic digestion") AND (("Ralstonia solanacearum") OR ("Burkholderia solanacearum") OR ("Bacillus solanacearum") OR ("Pseudomonas solanacearum") OR ("Pseudomonas batatae") OR ("Pseudomonas ricini"))	WoS	5	0	5	1	4	0	4

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#13	(("Thermal inactivation") OR ("Heat treatment")) AND (("Clavibacter michiganensis") OR ("Aplanobacter michiganense") OR ("Bacterium michiganense") OR ("Corynebacterium michiganense") OR ("Mycobacterium flavum subsp. michiganense") OR ("Phytomonas michiganensis") OR ("Pseudomonas michiganensis"))	WoS	18	0	18	10	8	0	8
#14	(compost*) AND (("Clavibacter michiganensis") OR ("Aplanobacter michiganense") OR ("Bacterium michiganense") OR ("Corynebacterium michiganense") OR ("Mycobacterium flavum subsp. michiganense") OR ("Phytomonas michiganensis") OR ("Pseudomonas michiganensis"))	WoS	19	0	19	14	5	1	4

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#15	("anaerobic digestion") AND (("Clavibacter michiganensis") OR ("Aplanobacter michiganense") OR ("Bacterium michiganense") OR ("Corynebacterium michiganense") OR ("Mycobacterium flavum subsp. Michiganense") OR ("Phytomonas michiganensis") OR ("Pseudomonas michiganensis"))	WoS	4	0	4	1	3	0	3
#16	(("Thermal inactivation") OR ("Heat treatment")) AND (("Phytophthora sp.") OR ("Phytophtora sp.") OR ("Phytophtora ramorum"))	WoS	5	0	5	5	0	0	0
#17	(compost*) AND (("Phytophthora sp.") OR ("Phytophtora sp.") OR ("Phytophtora ramorum"))	WoS	22	0	22	21	1	0	1
#18	("anaerobic digestion") AND (("Phytophthora sp.") OR ("Phytophtora sp.") OR ("Phytophtora ramorum"))	WoS	0	0	0	0	0	0	0

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#19	(("Thermal inactivation") OR ("Heat treatment")) AND (("Fusarium oxysporum") OR ("Fusarium sp."))	WoS	205	0	205	171	34	0	34
#20	(compost*) AND (("Fusarium oxysporum") OR ("Fusarium sp."))	WoS	738	0	738	572	166	0	166
#21	("anaerobic digestion") AND (("Fusarium oxysporum") OR ("Fusarium sp."))	WoS	15	0	15	4	11	0	11
#22	(("Thermal inactivation") OR ("Heat treatment")) AND (("Penicillium expansum") OR ("Penicillium sp.") OR ("Penicillium crustaceum") OR ("Penicillium glaucum"))	WoS	145	0	145	122	23	0	23
#23	(compost*) AND (("Penicillium expansum") OR ("Penicillium sp.") OR ("Penicillium crustaceum") OR ("Penicillium glaucum"))	WoS	108	0	108	86	22	0	22
#24	("anaerobic digestion") AND (("Penicillium expansum") OR ("Penicillium sp.") OR ("Penicillium crustaceum") OR ("Penicillium glaucum"))	WoS	8	0	8	6	2	0	2

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#25	(("Thermal inactivation") OR ("Heat treatment")) AND ((”Aspergillus niger var. niger”) OR (”Aspergillopsis nigra”) OR (”Rhopalocystis nigra”) OR (”Sterigmatocystis nigra”) OR (”Aspergillus sp.”))	WoS	20	0	20	15	5	0	5
#26	(compost*) AND ((”Aspergillus niger var. niger”) OR (”Aspergillopsis nigra”) OR (”Rhopalocystis nigra”) OR (”Sterigmatocystis nigra”) OR (”Aspergillus sp.”))	WoS	77	0	77	61	16	0	16
#27	("anaerobic digestion") AND ((”Aspergillus niger var. niger”) OR (”Aspergillopsis nigra”) OR (”Rhopalocystis nigra”) OR (”Sterigmatocystis nigra”) OR (”Aspergillus sp.”))	WoS	4	0	4	1	3	0	3
#28	(("Thermal inactivation") OR ("Heat treatment")) AND ((”Olpidium brassicae”) OR (“Asterocystis radices”) OR (“Chytridium brassicae”) OR (“Olpidiaster radices”) OR (“Pleotrachelus brassicae") OR (“Olpidium sp.”))	WoS	7	0	7	4	3	0	3

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#29	(compost*) AND ((”Olpidium brassicae”) OR (“Asterocystis radices”) OR (“Chytridium brassicae”) OR (“Olpidiaster radices”) OR (“Pleotrachelus brassicae") OR (“Olpidium sp.”))	WoS	11	0	11	6	5	0	5
#30	("anaerobic digestion") AND ((”Olpidium brassicae”) OR (“Asterocystis radices”) OR (“Chytridium brassicae”) OR (“Olpidiaster radices”) OR (“Pleotrachelus brassicae") OR (“Olpidium sp.”))	WoS	0	0	0	0	0	0	0
#31	(("Thermal inactivation") OR ("Heat treatment")) AND ((“Synchytrium endobioticum”) OR (Potato wart disease))	WoS	10	0	10	9	1	0	1
#32	(compost*) AND ((“Synchytrium endobioticum”) OR (Potato wart disease))	WoS	37	0	37	23	14	0	14
#33	("anaerobic digestion") AND ((“Synchytrium endobioticum”) OR (Potato wart disease))	WoS	4	0	4	1	3	0	3
#34	(("Thermal inactivation") OR ("Heat treatment")) AND (("Sclerotinia sp.") OR ("Sclerotinia minor") OR ("Sclerotinia sclerotiorum"))	WoS	37	0	37	32	5	0	5

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#35	(compost*) AND (("Sclerotinia sp.") OR ("Sclerotinia minor") OR ("Sclerotinia sclerotiorum"))	WoS	130	0	130	109	21	0	21
#36	("anaerobic digestion") AND (("Sclerotinia sp.") OR ("Sclerotinia minor") OR ("Sclerotinia sclerotiorum"))	WoS	9	0	9	0	9	0	9
#37	(("Thermal inactivation") OR ("Heat treatment")) AND (Meloidogyne)	WoS	87	0	87	55	32	0	32
#38	(compost*) AND (Meloidogyne)	WoS	421	0	421	337	84	0	84
#39	("anaerobic digestion") AND (Meloidogyne)	WoS	6	0	6	2	4	0	4
#40	(("Thermal inactivation") OR ("Heat treatment")) AND (Globodera)	WoS	19	0	19	14	5	0	5
#41	(compost*) AND (Globodera)	WoS	63	0	63	52	11	0	11
#42	("anaerobic digestion") AND (Globodera)	WoS	7	0	7	0	7	0	7
#43	(("Thermal inactivation") OR ("Heat treatment")) AND ((Tobamovirus) OR ("Tobacco Mosaic Virus") OR ("TMV"))	WoS	273	0	273	247	26	0	26

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#44	(compost*) AND ((Tobamovirus) OR ("Tobacco Mosaic Virus") OR ("TMV"))	WoS	89	0	89	66	23	0	23
#45	("anaerobic digestion") AND ((Tobamovirus) OR ("Tobacco Mosaic Virus") OR ("TMV"))	WoS	7	0	7	3	4	0	4
#46	(("Thermal inactivation") OR ("Heat treatment")) AND (("Salmonella Senftenberg") OR (Salmonella))	WoS	259	0	259	237	22	0	22
#47	(compost*) AND (("Salmonella Senftenberg") OR (Salmonella))	WoS	256	0	256	214	42	0	42
#48	("anaerobic digestion") AND (("Salmonella Senftenberg") OR (Salmonella))	WoS	82	0	82	30	52	0	52
#49	(("Thermal inactivation") OR ("Heat treatment")) AND ("Enterococcus faecalis")	WoS	40	0	40	32	8	0	8
#50	(compost*) AND ("Enterococcus faecalis")	WoS	46	0	46	42	4	0	4
#51	("anaerobic digestion") AND ("Enterococcus faecalis")	WoS	15	0	15	7	8	0	8
#52	(("Thermal inactivation") OR ("Heat treatment")) AND ("Ascaris suum") AND (eggs)	WoS	15	0	15	3	12	0	12
#53	(compost*) AND ("Ascaris suum") AND (eggs)	WoS	53	0	53	23	30	0	30

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#54	("anaerobic digestion") AND ("Ascaris suum") AND (eggs)	WoS	0	0	0	0	0	0	0
#55	(("Thermal inactivation") OR ("Heat treatment")) AND (("Leptinotarsa decemlineata") OR ("colorado potato beetle"))	WoS	3	0	3	0	3	0	3
#56	(compost*) AND (("Leptinotarsa decemlineata") OR ("colorado potato beetle"))	WoS	15	0	15	15	0	0	0
#57	("anaerobic digestion") AND (("Leptinotarsa decemlineata") OR ("colorado potato beetle"))	WoS	0	0	0	0	0	0	0
#58	(("Thermal inactivation") OR ("Heat treatment")) AND (("Popillia japonica") OR ("Japanese beetle"))	WoS	3	0	3	2	1	0	1
#59	(compost*) AND (("Popillia japonica") OR ("Japanese beetle"))	WoS	18	0	18	15	3	0	3
#60	("anaerobic digestion") AND (("Popillia japonica") OR ("Japanese beetle"))	WoS	0	0	0	0	0	0	0

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#61	(("Thermal inactivation") OR ("Heat treatment")) AND (("Anoplophora glabripennis") OR ("Asian long-horned beetle") OR ("sky beetle") OR ("Starry sky beetle") OR (ALB))	WoS	51	0	51	44	7	0	7
#62	(compost*) AND(("Anoplophora glabripennis") OR ("Asian long-horned beetle") OR ("sky beetle") OR (Starry sky beetle") OR (ALB))	WoS	0	0	0	0	0	0	0
#63	("anaerobic digestion") AND (("Anoplophora glabripennis") OR ("Asian long-horned beetle") OR ("sky beetle") OR (Starry sky beetle") OR (ALB))	WoS	0	0	0	0	0	0	0
#64	(("Thermal inactivation") OR ("Heat treatment")) AND (Xiphinema)	WoS	22	0	22	22	0	0	0
#65	(compost*) AND (Xiphinema)	WoS	28	0	28	28	0	0	0
#66	("anaerobic digestion") AND (Xiphinema)	WoS	0	0	0	0	0	0	0
#67	(("Thermal inactivation") OR ("Heat treatment")) AND (("Plasmodiophora brassicae") OR ("Clubroot"))	WoS	0	0	0	0	0	0	0

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#68	(compost*) AND (("Plasmodiophora brassicae") OR ("Clubroot"))	WoS	16	0	16	6	10	0	10
#69	("anaerobic digestion") AND (("Plasmodiophora brassicae") OR ("Clubroot"))	WoS	4	0	4	0	4	0	4
#70	(("Thermal inactivation") OR ("Heat treatment")) AND (("Tilletia indica") OR ("karnal bunt") OR ("partial bunt"))	WoS	0	0	0	0	0	0	0
#71	(compost*) AND (("Tilletia indica") OR ("karnal bunt") OR ("partial bunt"))	WoS	0	0	0	0	0	0	0
#72	("anaerobic digestion") AND (("Tilletia indica") OR ("karnal bunt") OR ("partial bunt"))	WoS	0	0	0	0	0	0	0
#73	(("Thermal inactivation") OR ("Heat treatment")) AND (("Streptomyces scabies") OR ("Streptomyces scabiei") OR ("Oospora scabies ") OR ("Actinomyces scabies "))	WoS	1	0	1	1	0	0	0
#74	(compost*) AND (("Streptomyces scabies") OR ("Streptomyces scabiei") OR ("Oospora scabies ") OR ("Actinomyces scabies "))	WoS	5	0	5	5	0	0	0

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#75	("anaerobic digestion") AND (("Streptomyces scabies") OR ("Streptomyces scabiei") OR ("Oospora scabies ") OR ("Actinomyces scabies "))	WoS	0	0	0	0	0	0	0
#76	(("Thermal inactivation") OR ("Heat treatment")) AND ("Phytophthora rubi")	WoS	1	0	1	0	1	0	1
#77	(compost*) AND ("Phytophthora rubi")	WoS	0	0	0	0	0	0	0
#78	("anaerobic digestion") AND ("Phytophthora rubi")	WoS	0	0	0	0	0	0	0
#79	(("Thermal inactivation") OR ("Heat treatment")) AND (("Phytophthora fragariae") OR ("Lanarkshire disease"))	WoS	4	0	4	4	0	0	0
#80	(compost*) AND (("Phytophthora fragariae") OR ("Lanarkshire disease"))	WoS	22	0	22	16	6	0	6
#81	("anaerobic digestion") AND (("Phytophthora fragariae") OR ("Lanarkshire disease"))	WoS	0	0	0	0	0	0	0

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#82	(("Thermal inactivation") OR ("Heat treatment")) AND ("Clavibacter sepedonicus") OR ("Clavibacter michiganensis subsp. Sepedonicus") OR ("Corynebacterium michiganense subsp. Sepedonicum") OR ("Corynebacterium sepedonicum") OR ("bacterial ring rot of potato") OR ("ring rot of potato"))	WoS	7	0	7	2	5	0	5
#83	(compost*) AND ("Clavibacter sepedonicus") OR ("Clavibacter michiganensis subsp. Sepedonicus") OR ("Corynebacterium michiganense subsp. Sepedonicum") OR ("Corynebacterium sepedonicum") OR ("bacterial ring rot of potato") OR ("ring rot of potato"))	WoS	4	0	4	2	2	0	2
#84	("anaerobic digestion") AND (("Clavibacter sepedonicus") OR ("Clavibacter michiganensis subsp. Sepedonicus") OR ("Corynebacterium michiganense subsp. Sepedonicum") OR ("Corynebacterium sepedonicum") OR ("bacterial ring rot of potato") OR ("ring rot of potato"))	WoS	3	0	3	1	2	0	2

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#85	(("Thermal inactivation") OR ("Heat treatment")) AND ("Dickeya")	WoS	7	0	7	6	1	0	1
#86	(compost*) AND ("Dickeya")	WoS	0	0	0	0	0	0	0
#87	("anaerobic digestion") AND ("Dickeya")	WoS	0	0	0	0	0	0	0
#88	(("Thermal inactivation") OR ("Heat treatment")) AND ("Pospiviroid")	WoS	21	0	21	21	0	0	0
#89	(compost*) AND ("Pospiviroid")	WoS	1	0	1	0	1	0	1
#90	("anaerobic digestion") AND ("Pospiviroid")	WoS	0	0	0	0	0	0	0
#91	(("Thermal inactivation") OR ("Heat treatment")) AND (("Arion vulgaris") OR ("Spanish slug"))	WoS	0	0	0	0	0	0	0
#92	(compost*) AND (("Arion vulgaris") OR ("Spanish slug"))	WoS	1	0	1	1	0	0	0
#93	("anaerobic digestion") AND(("Arion vulgaris") OR ("Spanish slug"))	WoS	0	0	0	0	0	0	0
#94	(("Thermal inactivation") OR ("Heat treatment")) AND (("Arion lusitanicus") OR ("Arion rufus var. vulgaris") OR ("Arion lusitanicus auct. non Mabille") OR ("Spanish slug"))		0			0			

Search ID	Search term	Data-base	Records identified	Records removed duplicates	Records screened	Records excluded	Full text articles assessed for eligibility	Full text articles excluded	Full text articles included in review
#95	(compost*) AND (("Arion lusitanicus") OR ("Arion rufus var. vulgaris") OR ("Arion lusitanicus auct. non Mabille") OR ("Spanish slug"))	WoS	4	0	4	2	2	0	2
#96	("anaerobic digestion") AND (("Arion lusitanicus") OR ("Arion rufus var. vulgaris") OR ("Arion lusitanicus auct. non Mabille") OR ("Spanish slug"))	WoS	1	0	1	0	1	0	1

Appendix III

Supplementary Table 1. Some regulations relevant for the different groups of organic wastes depicted for this report

Organic waste group	Legislation
Park and garden waste	The regulation on alien organisms; FOR-2015-06-19-716 The regulation of fertiliser products; FOR-2003-07-04-951 The regulation on plant health; FOR-2000-12-01-1333
Wasted plants and debris from garden centers	The regulation on plant health; FOR-2000-12-01-1333 The regulation of fertiliser products; FOR-2003-07-04-951 The regulation on alien organisms; FOR-2015-06-19-716
Food waste	The regulation on animal byproducts; FOR-2016-09-14-1064 The regulation on alien organisms; FOR-2015-06-19-716 The regulation on plant health; FOR-2000-12-01-1333 The regulation of fertiliser products; FOR-2003-07-04-951 The regulation on alien organisms; FOR-2015-06-19-716
Wastes from the food and animal feed industry	The regulation on plant health; FOR-2000-12-01-1333 The regulation on animal byproducts; FOR-2016-09-14-1064 The regulation of fertiliser products; FOR-2003-07-04-951 Regulations on measures against Phytophthora ramorum; FOR-2003-03-17-341
Manure	The regulation on plant health; FOR-2000-12-01-1333 The regulation on wild oats; FOR-2015-06-22-752 The regulation on animal byproducts; FOR-2016-09-14-1064 The regulation of fertiliser products; FOR-2003-07-04-951
Bulking agents	The regulation on plant health; FOR-2000-12-01-1333 The regulation on alien organisms; FOR-2015-06-19-716 The regulation of fertiliser products; FOR-2003-07-04-951

Organic waste group	Legislation
Husks and seeds from contracted grain and seed husk cleaners	The regulation on wild oats; FOR-2015-06-22-752 The regulation of fertiliser products; FOR-2003-07-04-951 The regulation on plant health; FOR-2000-12-01-1333

Appendix IV

Fourty-four non-woody vascular plant species listed on the Norwegian Alien Species List (Artsdatabanken, 2018) as "particularly high risk" (svært høy risiko).

Scientific name	**Norwegian name**
Barbarea vulgaris	vinterkarse
Bunias orientalis	russekål
Elodea canadensis	vasspest
Elodea nuttallii	smal vasspest
Lactuca serriola	taggsalat
Lupinus nootkatensis	sandlupin
Symphytum officinale	valurt
Reynoutria ×bohemica	hybridslirekne
Vincetoxicum rossicum	russesvalerot
Epilobium ciliatum ciliatum	ugrasmjølke
Epilobium ciliatum glandulosum	alaskamjølke
Aruncus dioicus	skogskjegg
Lamiastrum galeobdolon argentatum	sølvtvetann
Lamiastrum galeobdolon galeobdolon	parkgulltvetann
Lysimachia punctata	fagerfredløs
Pastinaca sativa hortensis	hagepastinakk
Lysimachia nummularia	krypfredløs
Arctium tomentosum	ullborre
Lupinus polyphyllus	hagelupin
Rorippa ×armoracioides	hybridkulekarse
Bromopsis inermis	bladfaks
Cerastium tomentosum	filtarve
Heracleum mantegazzianum	kjempebjørnekjeks
Heracleum persicum	tromsøpalme
Melilotus albus	hvitsteinkløver
Petasites japonicus giganteus	japanpestrot

Petasites hybridus	legepestrot
Phedimus spurius	gravbergknapp
Primula elatior elatior	lundnøkleblom
Reynoutria sachalinensis	kjempeslirekne
Senecio viscosus	klistersvineblom
Vinca minor	gravmyrt
Senecio inaequidens	boersvineblom
Melilotus officinalis	legesteinkløver
Odontites vulgaris	engrødtopp
Solidago canadensis	kanadagullris
Festuca rubra commutata	veirødsvingel
Berteroa incana	hvitdodre
Impatiens glandulifera	kjempespringfrø
Impatiens parviflora	mongolspringfrø
Myrrhis odorata	spansk kjørvel
Phedimus hybridus	sibirbergknapp
Reynoutria japonica	parkslirekne
Alchemilla mollis	praktmarikåpe