Review Article

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Research in biodynamic food and farming – a review

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Abstract: Research into biodynamic food and farming has a long history within the biodynamic movement. Whilst the basic aim of this research has always been to provide knowledge for furthering the development of this farming approach, recently interest has increased in sharing research activities and results with the global scientific community. After commencing with an introduction to biodynamic agriculture, this review gives an overview of peer-reviewed publications on issues in biodynamic food and farming that have been published between 2006 and 2017. The time before this period is covered by the reviews of Leiber et al. (2006) and Turinek et al. (2009).

Overall, 86 articles were included into this review. The most recognized topics were soil quality and soil health in biodynamic vs. conventional and organic farming, effects of biodynamic preparations, food quality, and viticulture. The studies provide substantial evidence for positive effects of biodynamic management on agroecosystems and food quality:

1) Biodynamic management creates system effects on soils, where compost application plays a crucial role.

2) Biodynamic preparations create effects on food chemical composition and food quality.

3) Biodynamic production can improve the value of food with regard to nutritive properties, taste and human health and well-being.

4) Biodynamic management improves grape quality and plant traits compared to non-biodynamic management.

Until now, the effects of biodynamic management have usually been studied with classical analytical methods in natural and life sciences through disciplinary and reductionist study designs. An application of study designs or specific methods that are conducive for a more holistic analysis are rarely implemented. Thus, we identify the development of appropriate methods and study designs for a holistic examination as a major challenge of future research in biodynamic food and farming.

Keywords: Biodynamic, farm organism, preparations, food quality, research methods

1 Introduction

From a historical point of view, Biodynamic Agriculture (BDA) has been the first systematic strategy of organic farming as an alternative to the emerging high-input industrial agriculture in early 20^{th}-century Europe. The biodynamic approach is based on eight lectures for farmers (‘*Spiritual Foundations for a Renewal of Agriculture: a Series of Lectures.*’) given by Rudolf Steiner in 1924 at Koberwitz farm near Wrocław (formerly *Breslau*) (Steiner 1925, cf. Paull 2011). The concept of biodynamic farming has been developed in the context of anthroposophy (Paull 2011a, 2011b).

Today, biodynamic farming is practiced by more than 5.500 farmers worldwide (Demeter International, 2019), and the farming method has a very good reputation among consumers of organic products. Research to approve and develop biodynamic methods has always been an important concern of the community. Though, anthroposophy as a philosophical system takes a view on natural systems that departs in some points from the assumptions held by natural sciences. Biodynamic methods are therefore not

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fully comprehensible with classical natural sciences until now. Against this background, researchers in biodynamic food and farming were always interested to develop new analytical approaches in addition to classical natural science methods to support a more holistic exploration of biodynamic systems and methods. Biocrystallization is an example for a new analytical method that already gained reputation in the scientific literature (e.g. Fritz et al. 2011). However, biodynamic systems and techniques are usually studied with classical natural science methods until today, and there is a lot of evidence in the scientific literature in support of their effect, as shown in the review articles of Leiber et al. (2006) and Turinek et al. (2009).

The aim of this paper is to give an overview of current research in biodynamic food and farming, and to address challenges and perspectives in this field. We do that based on an overview of published articles in peer- reviewed scientific journals with a focus on the period from 2006 to 2017, continuing the work of Leiber et al. (2006) and Turinek et al. (2009).

2 Characteristics of biodynamic farming systems

2.1 The perception of the farm as an individual organism

In biodynamic agriculture, a farm is considered an organism with an own individuality. Steiner (1925) used man as a role model for the understanding of this farm organism. According to the concept, different elements of the farming system – such as arable fields, pastures, wild areas, the soil, the animals, the plants and the humans-hold the same functions as human body organs that are all vital for the individual farm as a whole. Biodynamic farm management should maintain or improve the health of this organism by supporting the function of all these organs, as well as of the relationships between them and the environment. As outlined by Bloksma and Struik (2007), a healthy farm organism in the biodynamic perspective is not only a physically ‘healthy’, resilient and sustainable, locally-adapted agroecosystem, but includes the socio-cultural and the mental/spiritual dimension, as farming in itself is an interaction between the human and the natural environment, and is embedded in a cultural environment.

2.2 Animals on the farm

The keeping of animals is an important requirement in biodynamic farming, as it is assumed that animals - and cows in particular - provide manure with a quality that cannot be reached with plant-based manure only. The Demeter Association therefore requires the keeping of ruminants on the farms in several countries. Further, cows should not be dehorned in biodynamic farming, and hornless breeds are avoided too. The reason is that the horn is considered a fundamental trait of bovines that should not be eradicated for management reasons. In fact, the horn has important functions in the cow’s organism (Knierim et al. 2015), and de-horning or missing horns alter the cow’s physiology considerably.

2.3 Soil management for living soils

Soil management in biodynamic farming aims at a healthy soil as central organ in the farm organism. According to Lehmann et al. (2015), a healthy soil can be defined as a resilient soil that is delivering soil-related ecosystem services at a high level. In principle, the concept of soil health in biodynamic farming does not differ from this definition, but it puts more weight on the ability of the soil to mediate or transform energetic impacts, such as cosmic forces (‘Cosmic forces’ here refers to an impact of the moon, the sun and the planets, as well as the lunar or zodiac cycles on life processes), or the biodynamic preparations.

2.4 The preparations

The biodynamic preparations are often considered the core element of biodynamic farming. These amendments shall impulse the soil in a way comparable to homeopathic practice. There are nine defined preparations that consist of plant materials, manure, or silica sand, contained in covers of animal organs. The production of these preparations could be understood as similar to producing household remedies using ingredients from the farm. Although the preparations are not easily comprehensible from a scientific point of view, there is a lot of evidence for the effectivity of the preparations in contemporary scientific literature, as will be shown later in this review.

2.5 Breeding

The breeding of robust plants and animals for a high product quality has always been an important concern in biodynamic farming. The abandonment of manipulative techniques such as hybrid breeding, the consideration of biodynamic cultivation measures, and an orientation towards ripeness, vitality and taste are essential characteristics of biodynamic plant breeding.

2.6 Food for health and well-being

Biodynamic farming should produce food and feedstuffs of high quality. The aim of biodynamic agriculture is to produce products that nourish not only the body but also the soul and spirit and thus promote human development (Demeter International 2016). The nourishment of the soul and spirit is a claim that is up to now only poorly proved due to a lack of methods and research. However, results on consumer choice (e.g. Goetzke et al. (2014) and food-related emotional well-being (Geier et al. 2016), may be considered as hints towards properties of food beyond nutritional effects.

3 Research methods in biodynamic farming

Research into biodynamic farming has a long history. The 'Agricultural Experimental Circle ('Landwirtschaftlicher Versuchsring') was founded in the German-speaking countries directly after Steiner's lectures at Koberwitz in 1924, in order to examine the assumptions and recommendations through on-farm experiments. As the biodynamic view on farming explicitly calls for a holistic perspective, common reductionist approaches to the assessment of farm management effects have been considered insufficient by the biodynamic research community. However, research in the context of systems, either traditional as well as academic ecological knowledge systems, considers both holistic and reductionist aspects as important (Ludwig and Poliseli 2018). According to the authors, neither knowledge system can fully understand an object in the natural world relying on only one of the two methodological approaches. However, traditional knowledge systems usually set the focus on a holistic perspective, as this is inevitable in farming practice to cope with a challenge. Academic research, on the other hand, basically aims at the production of new knowledge on different scales and often needs to set the focus on a reductionist assessment to reduce complexity.

Even though biodynamic farming theory has been newly invented roughly a hundred years ago, it shares many characteristics with traditional knowledge systems, and the argumentation of Ludwig and Poliseli (2018) is therefore helpful to understand the biodynamic knowledge system, too.

An approach to a holistic analysis of soil, plant and food samples is the application of picture-forming methods. With these methods, an extract from a sample is put on a filter paper (circular chromatography, e.g. Kokornaczyk et al. 2017) or on a round plate with copper chloride $CuCl_2$ (Biocrystallization, e.g. Huber et al. 2010), where characteristic patterns occur. The biocrystallization method has successfully been applied to differentiate between samples of different origin in replicated experiments (e.g. Kahl et al. 2009; Busscher et al. 2010). Recently, it has been shown that these crystallization patterns can be related to the physiological age of plant samples (Doesburg et al. 2015; Fritz et al. 2018). In principal, biocrystallization has some similarities with gas chromatography. The analysis takes place on a high level of integration. Detectable effects on that level may not be accessible with a reductionist approach, even though correlations between biocrystallization pattern and single biochemical characteristics should exist, if the effective biochemical compound or process that impacts on the formation of the pattern has been fully identified. A study that shows links between circular chromatography pattern and selected chemical soil parameters has been presented by Kokornaczyk et al. (2017). However, in contrast to gas chromatography and comparable approaches, it is assumed that crystallization patterns do not only express the chemical composition of a sample. Instead, they shall give a complex picture of the physiological state of an object that includes a link to vitality and health beyond chemical characteristics.

Another holistic approach is the 'Empathic Food Test' according to Geier et al. (2016), which is a method for the evaluation of food-induced emotions. The protocol of the method builds on sensory food testing, but relates to emotions instead of taste. By doing so, the method links food quality to human well-being.

4 Methods

A comprehensive literature research was conducted based on the Google Scholar online search engine (http://

scholar.google.com). The main search keyword was "biodynamic". The focus of the research was set on peer reviewed publications from 2006 until 2017. This period was chosen because it follows on from the review article "Biodynamic Agriculture Today" by Leiber et al. (2006) and overlaps marginally with the review article by Turinek et al. (2009).

We included 86 papers in this review. According to Figure 1, there is a clear trend towards increasing publication activity over the survey period.

The majority of the articles (67 papers) relate to studies carried out in Europe. In addition, 4 papers come from the region of Australia/New Zealand, 4 papers from North America and 4 from South America, while 7 papers originate in South East Asia. We could not find any papers from Africa in the survey period.

Publications could be clustered into six topics (Figure 2): twenty-one papers relate to aspects of soil quality and health, 15 papers address effects of the biodynamic preparations, 20 papers are on food quality, 18 regular papers and one review papers deal with aspects in viticulture and enology, and 5 papers each address the sustainability of biodynamic farming systems, the development of the sector, and issues in biodynamic crop production. The total number of citations (90) is slightly higher than the number of references (86), as single references may appear in more than one thematic group.

The thematic perspective of the papers thus does not cover all characteristics of biodynamic agriculture introduced above. This issue will be discussed later on.

5 Results

5.1 State of the art

Before this review, two other reviews on research into biodynamic agriculture in general have been published (Turinek et al. 2009; Leiber et al. 2006), as well as one review about research into biodynamic wine production (Castellini et al. 2017), and one about biodynamic preparation effects (Chalker-Scott 2013).

Leiber et al. (2006) focus on a general description of biodynamic agriculture and its characteristic elements. Furthermore they give an overview on the main question of biodynamic researchers and farmers. This review shows that early research mainly focuses on the mode of actions of the biodynamic preparations, the impact of the biodynamic approach on the soil and influence of the cosmic rhythms on the development of plants. Turinek et al. (2009) summarize the results of different long term trials. These studies concern the influence of the biodynamic approach on chemical, physical and biological properties of the soil. Furthermore the review shows that research analyses the influence of biodynamic agriculture on biodiversity and environmental factors. An overview of case studies concerning biodynamic topics is also given. Biocrystallization is stated as a promising method for quality assessment in biodynamic farming.

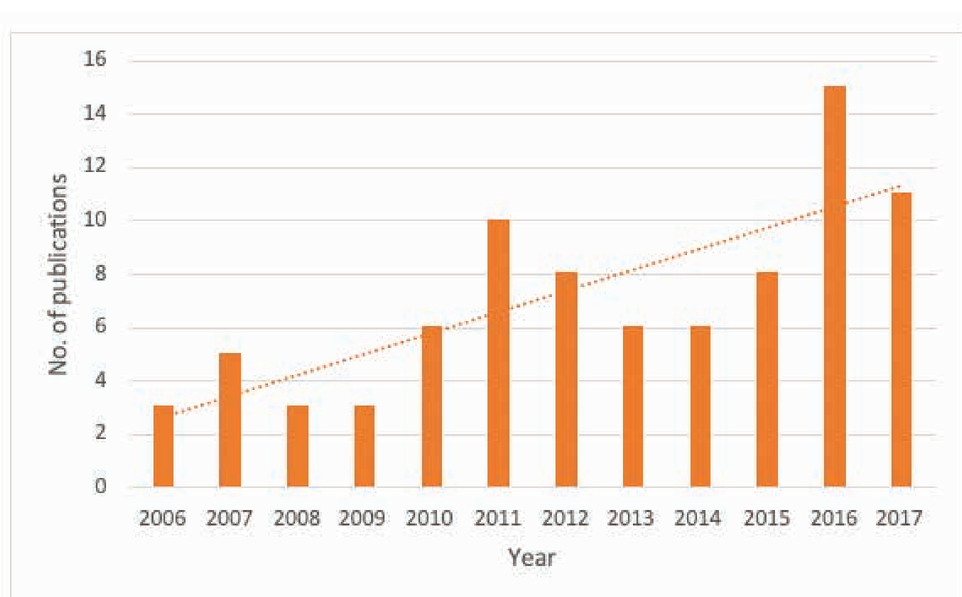

Figure 1: Temporal development and trend of the number of peer-reviewed publications on biodynamic food and farming in the scientific literature 2006-2017

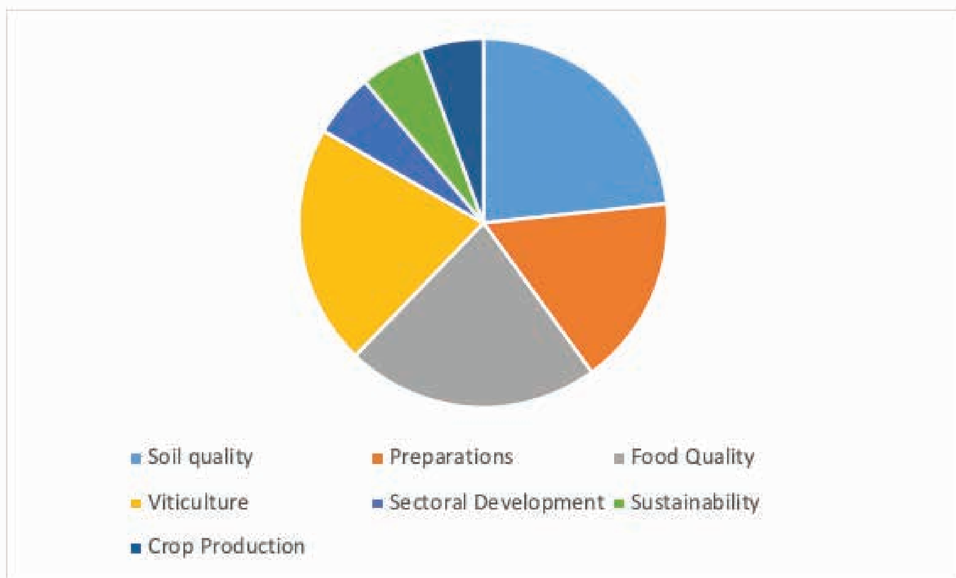

Figure 2: Thematic distribution of peer-reviewed publications in biodynamic food and farming. Note: Single articles appear in all thematic clusters they address

5.2 Soil quality and soil health

Although the soil and soil management receives much attention in biodynamic farming practice, as well as in research on farming systems, there are only few studies on soil-related issues in biodynamic farming available in the scientific literature (cf. also Turinek et al. 2009; Ponzio et al. 2013). These studies focus on the effects of biodynamic management on soil organic matter, soil biology, and/or nutrient availability, applying classical analytical methods in soil science. Most papers included in this review relate to three long-term field experiments: the DOC experiment at Therwil/Switzerland that has been running since 1977, the experiment at Darmstadt/Germany that has been conducted from 1980 to 2009, and the experiment at Frick/Switzerland that was started in 2002 and still continues. The setup of the DOC experiment is a comparison of farming systems with regard to fertilization and crop protection on the basis of a regular crop rotation (cf. description in Fließbach et al. 2007). The trial at Darmstadt compared biodynamic management to organic management (where the difference consisted of the application of biodynamic preparations in the biodynamic treatment) and to a non-organic treatment without the application of organic manure, but with synthetic N-fertilizer application (Raupp and Oltmanns 2006). The Frick experiment is a three-factorial experiment, where the effect of biodynamic management (i.e. application of preparations) is compared on the basis of different levels of fertilization and tillage intensity (Berner et al. 2008).

The only two studies included here that are not based on the long-term field experiments denoted above are a paired-farm survey in Australia (Burkitt et al. 2007), and an investigation of vineyards under different management by Burns et al. (2016).

Soil organic matter (SOM) is recognized as a key factor of soil fertility, and of many soil functions (e.g. Fageria 2012). Higher SOM levels under biodynamic management compared to all non-biodynamic treatments have been reported from the DOC experiment (Fließbach et al. 2007). At Darmstadt, SOM levels under biodynamic management were also higher than under non-biodynamic management according to Heitkamp et al. (2011), but the authors suspect that the difference from the non-biodynamic (organic) treatment that received the same amount of manure (without biodynamic preparations) is a result of the investigative procedure. No difference in SOM levels between biodynamic and non-biodynamic management was observed in the Frick experiment (Gadermaier et al. 2012), nor in the survey of pasture soils by Burkitt et al. (2007).

In the DOC experiment, biodynamic management, further, led to a higher proportion of more stable organic matter fractions (Birkhofer et al. 2007), higher biological activity (Birkhofer et al. 2007; Fließbach et al. 2007), a change in bacterial populations (Heger et al. 2012), and a better utilization of carbon by the microbial biomass (Fließbach et al. 2007) compared to the non-biodynamic treatments. Changes in bacterial populations (Faust et al. 2017; Joergensen et al. 2009) and a more efficient use of soil organic carbon by microbes (Sradnick et al. 2018) were also reported from the experiment at Darmstadt. At Frick, biodynamic management also had an impact on the soil microbial community (Gadermaier et al. 2012; Hartmann et al. 2015). In their study in vineyard soils, Burns et al. (2016) found that microbial diversity and community structures were not affected by the management system *per se* (biodynamic vs. organic vs. conventional), but by specific management elements, and cover crops in particular.

Taking into account the effective difference between management systems compared in the different studies, the effect of biodynamic farming on soil properties must be considered first of all a complex system effect. The strongest effect on the system is caused by the application of animal manure, usually in the form of compost, irrespectively of the farming system.

Results from the Darmstadt and Frick long-term field experiments provide evidence for an effect of the biodynamic preparations on soil biological properties and processes, indicating the need for further investigation in this field. In the search for an explanation of the preparation effects, Giannattasio et al. (2013) supposed that the material and microbial properties of the horn manure preparation may impact on the regulatory effects of auxins on soil processes. Radha and Rao (2014) further assume that the bacterial and fungal populations in biodynamic preparations may increase the availability of phosphorus to plants.

The soil, and soil fertility in particular, has always received much attention in organic farming. As stated in the introduction, soil management in biodynamic farming aims at a healthy 'soil organ' in the farm organism. Until now, the majority of studies on management effects on agricultural soils - not only in biodynamic agriculture - focus on the impact on soil properties, but not on the performance of soil functions or ecological services.

5.3 Biodynamic preparations

The biodynamic preparations are an important element of the biodynamic approach and a key feature that differentiates the biodynamic from the organic approach. Sharma et al. (2012) found that the amount of cumin seeds (*Cuminum cyminum*) was significantly increased more than 30% by the application of horn manure and horn silica for two variations of fertilization. In a trial in Vietnam, the yield of two different varieties of soybean (Glycine max) increased 30% through the application of biodynamic preparations compared to the control without preparations (Tung and Ferandez 2007). Neither the control nor the treated variant was fertilized. Also the yield of two rice (*Oryza sativa*) varieties increased by 15% and 20% through the application of biodynamic preparations without fertilization (Valdez and Fernandez 2008). Valdez and Fernandez (2008) showed in the same study that the root length, root weight, sprouting weight as well as the available phosphorus increased (plus 20%) after harvest through the application of biodynamic preparations compared to untreated plants. The application of horn silica increased the yield of black gram (*Vigna mungo*) cultivated under organic conditions without fertilization by 27% compared to the treatment without horn silica (Trivedi et al. 2013). The net photosynthesis activity of all three pumpkin (*Cucurbita pepo*) varieties and two out of three potato (*Solanum tuberosum*) varieties was significantly increased with horn manure and horn silica treatment (Juknevičienė 2015, Vaitkevičienė 2016). Seed quality of dwarf beans (*Phaseolus vulgaris*) in germination tests was enhanced by treatments of the parent plants with horn silica applications (Fritz et al. 2005).

No significant differences in yield have been found for salad (*Lactuca sativa*) after the application of compost and spray preparations in three variations of fertilization (Bacchus 2010). Also Jayasree and George (2006) found no significant effect on the development of chili plants (*Capsicum annuum*) through the application of biodynamic preparations.

The dehydrogenase activity in compost was significantly increased by the application of compost preparations (Reeve et al. 2010). The germination capacity of broad-leaved dock (*Rumex obtusfolius*) was with a germination capacity of 18% significantly lower in compost that had been treated with biodynamic preparations compared to the untreated compost where a germination capacity of 28% was detected (Zaller 2007). A high amount of bioactive substances and growth stimulating substances were detected in horn silica by Giannattasio et al. (2013) and Spaccini et al. (2012). Bacterial cultures that have been identified in horn silica were producers of auxin which had a significant growth-enhancing effect on corn (*Zea mais*) (Radha and Rao 2014). Jayachandran et al. (2016) analyzed the microbial load of the biodynamic preparation horn silica (501) and its activity against chosen rice (*Oryza sativa*) pathogens. *Bacillus spp*., *Bacillus amyloliquefaciens* and *Bacillus toyonensis* were identified as the main bacterial isolates. A strong antifungal effect was detected for *Baccillus amyloliquefaciens* against *R. solani* (Jayachandran et al. 2016). In the cultivation of pumpkin (*Cucurbita pepo*) and potatoes (*Solanum tuberosum*), the nitrogen, potassium, phosphorus, urease and sucrose activity in the soil were significantly increased over three test years of using horn manure treatment (Juknevičienė

2015 in Juknevičienė et al. 2019; Vaitkevičienė 2016 in Vaitkevičienė et al. 2019). Further influence of the preparations concerning food quality are described in the next section.

5.4 Food quality

Heimler et al. (2011) compared different production systems (conventional, organic and biodynamic) and found out that the highest content of polyphenol was found in Batavia lettuce (*Lactuca sativa* var. *capitata*) grown under biodynamic conditions. Polyphenols are desired secondary compounds in food that add to the nutritional value of products. Biodynamic red beet (*Beta vulgaris*) also had the highest total phenolic content followed by red beets grown under organic conditions and the lowest amount was found for conventional red beets (Bavec et al. 2010). Conversely the highest total phenolic content was found in organic mangoes (*Mangifera indica*) and not in biodynamic or conventional mangoes (Maciel et al. 2011). The concentration of total phenolic compounds and antioxidant activity DPPH increased significantly in potatoes (*Solanum tuberosum*) of the cultivar Red Emmalie and Blue Congo after the application of the biodynamic preparation horn silica (Jarienė et al. 2017). The total content of total anthocyanins and total phenolic increased in coloured-flesh potatoes (*Solanum tuberosum*) through the combined application of the biodynamic preparations horn manure and horn silica (Jarienė et al. 2015). No differences in polyphenolic content from different production systems was found for chicory (*Cichorium intybus*) (Heimler et al. 2009). Differences in nutritional quality and phenolic acid contents in tomatoes (*Solanum lycopersicum*) were rather caused by the year of production than from the farming system (conventional, organic and biodynamic) (D'Evoli et al. 2016). Masi et al. (2017) were able to differentiate the polyphenol content of biodynamic and conventional apples (*Malus domestica* var. *Golden Delicious*) but it was not possible to differentiate the samples regarding the volatile compounds. Three pumpkin (*Cucurbita pepo*) varieties had significantly higher antioxidant contents of lycopene, lutein and zeaxanthin with horn manure and horn silica treatment over three years of experiments (Juknevičienė 2015).

Heimler et al. (2009, 2011) showed that biodynamic chicory (*Cichorium intybus*) and Batavia lettuce (*Lactuca sativa* var. *capitata*) have a higher antioxidant activity than the same varieties from conventional and organic farming systems. Biodynamic red beet (*Beta vulgaris*, Bavec et al. 2010), biodynamic strawberries (*Fragaria spec.*, D'Evoli et al. 2010) as well as biodynamic mature green and ripe mangoes (*Mangifera indica*, Maciel et al. 2011) all had significant higher antioxidant activity than these products from conventional and organic farming systems.

Biodynamic cabbage (*Brassica oleracea*) contained more ascorbic acid than organic or conventional cabbage (Bavec et al. 2012). The same phenomenon was found for strawberries (*Fragaria spec.*, D'Evoli et al. 2010). Red beet (*Beta vulgaris*) from biodynamic production system showed the highest sugar content compared to red beets from organic, integrated and conventional production system (Bavec et al. 2010). Furthermore, Vaitkevičienė et al. (2016) detected that the starch content of coloured-flesh potatoes (*Solanum tuberosum*) increased significantly through the combined application of horn manure and horn silica.

No differences related to the approach of production were found by Langenkämper et al. (2006) who analyzed the nutritional value of wheat (*Triticum aestivum*). Rangel et al. (2011) investigated in the nutritional composition of lime juice (*Citrus latifolia*) and also detected no differences related to the production system. Yet Lucarini et al. (2012) analyzed the nitrate content of organic and biodynamic lettuce (*Lactuca sativa*) and red radicchio (*Cichorium intybus*) and concluded that the biodynamic variant had the lowest nitrate level.

Potatoes (*Solanum tuberosum*) from biodynamic cultivation in comparison to conventional cultivation were more positively related to traits such as quality indices, dry matter content, taste quality, relative proportion of pure protein and biocrystallization value (Kjellenberg and Granstedt 2015). Wheat (*Triticum aestivum*) from different fertilization systems of the DOC long-term field experiment were differentiated and classified with image forming methods. The indications of degeneration by aging in the image structures increased from biodynamic over organic to the conventional sample (Fritz et al. 2011).

In their comparison of milk from different management systems, Kusche et al. (2015) observed the highest share of nutritionally-valuable fatty acids in milk from biodynamic systems. Moreover it was proven in an encoded provocation test series that biodynamic raw milk has a better compatibility for children with food intolerances compared to pasteurized and homogenized milk from conventional production (Kusche 2015 in Abbring et al. 2019). The consumption of biodynamically manufactured dairy products lead to a higher fat quality of breast milk compared to the breast milk of women who consumed organic or conventional dairy products (Simões-Wüst et al. 2011). Newborn babies whose mothers mainly consumed biodynamically manufactured dairy products had a lower risk of contracting eczema (Thijs et al. 2011).

5.5 Enology and viticulture

The research area of biodynamic enology and viticulture has gained importance in recent years. A literature review by Castellini et al. (2017) outlines the biodynamic wine sector. It describes the definition and regulation of biodynamic wine production as well as the world wide biodynamic wine market. A long-term field experiment in Geisenheim, Germany, compares integrated, organic and biodynamic vineyard management and wine making. Biodynamic production resulted in lower yield, lower vigorous growth, lower pruning weight, lower grape cluster weight and less compact clusters and a lower presence of acetic acid compared to the integrated (Döring et al. 2015; Meissner 2015 in an article in Meissner et al. 2019). Organic management was between biodynmic and conventional for most parameters. Therefore, the three cultivation methods could be clearly differentiated in a main component analysis (Meissner et al. 2019). Biodynamic cultivation and organic cultivation differed only in the application of the preparations. Döring et al. (2015) also found less Botrytis in biodynamic production. No significant differences in bacterial and fungal communities in the different plots of the long-term experiment were detected, except for a higher abundance of Pseudomonas spp. and Alternaria alternata in biodynamic grapes compared to conventional (Kecskeméti et al. 2016). Meissner (2015 in Meissner et al. 2019) detected more earthworms in plots that have been cultivated biodynamically compared to organic and conventionally cultivated plots.

The quality of grape juice and wine from the long-term trial in Geisenheim was examined with the picture forming methods. A differentiation between grape juice from the integrated, organic and biodynamic production systems was already visible in the first year after conversion (Fritz et al. 2017). The assignment of grape juice samples (2006-2010) with help of the image forming methods was significant for all years (Meissner 2015 in Fritz et al. 2019, 2017). Samples from the biodynamic treatment showed a better physiological condition than those from the organic treatment, as indicated by the *ageing* sequence. Samples from the integrated treatment showed the highest age and corresponding degeneration. Botelho et al. (2016) found no differences between organic and biodynamic management when looking at grape yield and disease indices, but the natural defense compounds of biodynamic grapes appeared to be stimulated. Guzzon et al. (2016) concludes that biodynamic production systems positively affected the development of microbiota in years with difficult climatic conditions compared to conventional production. The fungal patterns in the vineyard were significantly influenced by the production systems, namely conventional and biodynamic, in the vineyard. However, no differences were found in the fungal patterns in the harvested grapes (Morrison-Whittle et al. 2017). The yeast microbiota of organic and biodynamic Sangiovese red wine varied independently of the production system (Patrignani et al. 2016).

Kokornaczyk et al. (2014) were able to differentiate organic and biodynamic wine using the droplet evaporation method and considering shape descriptors. In this method, the structures of the dried drops of the plant substance are examined. Several studies focus on chemical substances in wine. Some found no differences in the chemical composition between organic and conventional wine (Tassoni et al. 2013; Plahuta and Raspor 2007) whereas others were able to differentiate wine from organic and conventional production systems (Yañez et al. 2012, Granato et al. 2015). Some investigations succeeded in distinguishing between organic and biodynamic wine with regard to their chemical substances (Parpinello et al. 2015; Laghi et al. 2014; Picone et al. 2016). The method of 1H NMR (a nuclear magnetic resonance spectroscopy) seems to be a successful method for the differentiation of wine from different production systems (Laghi et al. 2014; Picone et al. 2016).

Ross et al. (2009) were able to differentiate organic and biodynamic wines by measure of sensory evaluation. Meissner (2015) was partly able to differentiate on a sensorial level, while no sensory differences between organic and biodynamic wine were found by Parpinello et al. (2015).

5.6 Sustainability

Five studies in our data base are related to sustainability in biodynamic farming systems. Turinek et al. (2010) and Bavec et al. (2010) analyzed the ecological food print of different production systems in a field trial in Slovenia. The biodynamic and organic systems showed over three years to have advantages over conventional in relation to environmental performance and ecological effectiveness related to energy use and climate impact. In the Czech Republic the efficiency of resources in biodynamic and organic farms was proved over conventional. A higher efficiency was found for organic farms (Pechrová and Vlašicová 2013). In Italy, according to the lifecycle assessment and energy analysis in integrated and biodynamic apricot orchards, the biodynamic production had a lower environmental impact and lower demand for energy (Pergola et al. 2016). Villanueva-Rey et al. (2014) considered the influence of viticulture production systems for the environment. This life cycle assessment in Spain indicated a lower environmental impact for the biodynamic production compared to conventional viticulture.

5.7 Development of biodynamic agriculture

Altogether four papers on the development of biodynamic agriculture have been published by Paull (2011a, 2011b, 2011c, 2014). These papers form excellent citable references on the concepts and development of this farming system.

The motivation of farmers to convert to biodynamic agriculture has been studied by Pechrová (2014).

5.8 Biodynamic crop production

Five papers in our data base address issues in biodynamic crop production. Three studies compared yields and plant quality in biodynamic and non-biodynamic cropping systems. The results are quite heterogenous: While Nabie et al. (2017) reported a significant increase of yields and nutritional traits in biodynamic compared to organic and conventionally cropped vegetables in a study carried out in India, Jakop et al. (2017) found that yields in biodynamic production of oil pumkins (*Cucurbita pepo*) could merely compete with those from conventional management. Maneva et al. (2017) compared plant health and yields in organically vs. biodynamically cropped kamut (*Triticum turgidum polonicum*) and observed significantly higher yields in the biodynamic treatment, even though no differences in phytosanitary parameters did occur.

Two papers deal with management techniques within biodynamic farming. Dudaš et al. (2016) analyzed basil (*Ocimum basilicum*) which has been sown according to the biodynamic planting calendar. Little effect on growth and quality parameters caused by the sowing date was found compared to the control. In the other study, no effects on seed production were caused by the application of a biodynamic method of weed suppression based on preparations from weed ash (Kirchoff 2016).

6 Discussion

6.1 Development of scientific publication activity in biodynamic food and farming

Research activities in biodynamic food and farming have for a long time been prioritised within the biodynamic community, with the aim of directly supporting the development of the sector. Researchers preferably used sectoral scientific journals and other media that have been well-established within the biodynamic community. The online data base Biodynamic-Research.net comprises more than 600 publications from the period 1924 until 2009, but less than hundred out of these have been published in peer-reviewed scientific journals.

The increasing number of articles in scientific journals indicates a growing interest of researchers in biodynamic food and farming to present their results to the scientific community.

To date, peer-reviewed publications on biodynamic food and farming cover the topics of soil management and soil health, effects of the biodynamic preparations, food quality, and oenology and viticulture. A small number of publications are also available on the topics of sustainability assessment and sectoral development. But until today, there is only one published study on the 'farm organism', even though this term is frequently used as an image to illustrate the interconnectedness of elements in a farm system even beyond biodynamic agriculture. In their study, Bloksma and Struik (2007) explore the applicability of the human as a role model for the design of farming systems on a theoretical basis. The authors try to apply the concept of human health and the diagnostic approach of physical/medical sciences in the assessment of farms, and conclude that the study of the farm organism must consider physical, socio-cultural and mental aspects.

And, even though animals are a key aspect of the biodynamic approach, no peer-reviewed articles from this research field appear in our review. In fact, there is a lot of research on animal-related aspects that is also of high interest with regard to biodynamic farming (e.g. Ebinghaus et al. 2017; Ivemeyer et al. 2011; Ivemeyer et al. 2014; Probst et al. 2012; Spengler Neff; Ivemeyer 2016). However, we found that these articles usually do not relate to biodynamic management as a factor in the experimental setup or study design, probably because biodynamic animal keeping has no unique management characteristics compared to crop production. Further, although more than 25 varieties of biodynamically bred cereal varieties are available today (cf. Meischner and Geier 2013), as well as more than 100 varieties of vegetables (cf. Kultursaat 2018), no scientific articles have been published on biodynamic breeding and varieties to date.

6.2 Effects of biodynamic management

With regard to soil health, eight out of ten studies report a positive system effect of biodynamic management on soil organic matter levels and biological parameters. This effect is mainly driven by organic fertilization, and it could be argued that the effect on soil properties may therefore not be related to biodynamic farming, as it could also be achieved in non-biodynamic systems. Even though this is true in principle, the situation reflects actual farming practice, where biodynamic management by its characteristic elements leads to the effect described above, when related to typical non-biodynamic management of today. However, studies from the Darmstadt long-term field experiment (Faust et al. 2017; Joergensen et al. 2009; Sradnick et al. 2018), as well as other studies that were published before the period of our review (e.g. Zaller and Koepke 2004) indicate that there may also be an impact of the biodynamic preparations on soil properties. Positive system effects of biodynamic management have also been observed in studies on sustainability issues.

Further, this paper describes 15 scientific studies directly focused on the effects of biodynamic preparations, from 2005 to 2017. In 13 of these studies, significant soil or plant reactions occurred with the application of biodynamic preparations. Only two studies found no significant soil or plant reaction. These results show that the biodynamic preparations have a significant effect. The conclusions of Chalker-Scott (2013) that no clear significant effects of the biodynamic preparations were determined (the significant effects that occurred were interpreted as random) was not confirmed in this literature review.

From the beginning, biodynamic management has always aimed at a high food quality. In fact, significant positive effects of biodynamic management on food quality have been reported in 17 studies included in this review. Only 4 studies found no differences. The effects on food quality were not only system effects, but were induced by the application of the biodynamic preparations in several cases.

Viticulture and wine making have become an important subject in biodynamic research for the success of the biodynamic approach in this field. The positive impact of biodynamic management is largely acknowledged among wine makers. In fact, differences between biodynamic and non-biodynamic management on viticultural systems and grape quality have been reported in 13 out of the 17 studies under review.

6.3 Researching biodynamic food and farming

Studies included in this review usually apply classical analytical methods from natural and life sciences to analyze biodynamic food and farming. Further, they usually follow a disciplinary reductionist approach, where the effect of treatments on specific target variables is examined. Yet, biodynamic farming itself takes a holistic and transdisciplinary perspective on effects on the whole organism, which may not be directly correlated to effects on single parameters.

Although different scientific investigation methods have been developed from the biodynamic movement (see section 3), they are only used to a limited extent in the scientific studies compiled here. In the sections on soil and on biodynamic preparations there is no study that includes holistic methods. In the section on food quality there are two studies (out of 21) that apply picture forming methods (Fritz et al. 2011; Kjellenberg and Gransted 2015). Among the studies on enology and viticulture there are 2 out of 19 studies using such methods, namely Kokornaczyk et al. (2014) with the droplet method and Fritz et al. (2017) with picture forming methods.

Another approach to a holistic assessment of effects in biodynamic food and farming could be taken by developing a conceptual framework that combines approved analytical methods in an appropriate transdisciplinary study design. For example, the assessment of the impact of agricultural management on food quality would not be based only on the chemical composition of a food crop, but could include a survey of the full chain of effect from crop production to the impact on human health and well-being.

7 Conclusions

The number of peer-reviewed studies in biodynamic food and farming is gradually increasing. These studies provide substantial evidence for the effects of biodynamic management on agroecosystems and food quality: the effects on soils are usually system effects of biodynamic management, where compost application plays a crucial role. The biodynamic preparations create measurable effects on food chemical composition and food quality. Further, biodynamic management as a whole, and the application of biodynamic preparations in particular, causes a differentiation between biodynamic and non-biodynamic vineyards.

To date, the effects of biodynamic management are usually studied with classical reductionist approaches in natural and life sciences using disciplinary and reductionist study designs. An application of study designs or specific methods for a more holistic analysis is rarely implemented. We identify the development of appropriate methods and study designs for a holistic examination as a major challenge of future research in biodynamic food and farming.

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