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Review

Review of Alternative Management Options of Vegetable Crop Residues to Reduce Nitrate Leaching in Intensive Vegetable Rotations

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Abstract: Vegetable crop residues take a particular position relative to arable crops due to often large amounts of biomass with a N content up to 200 kg N ha^{-1} left behind on the field. An important amount of vegetable crops are harvested during late autumn and despite decreasing soil temperatures during autumn, high rates of N mineralization and nitrification still occur. Vegetable crop residues may lead to considerable N losses through leaching during winter and pose a threat to meeting water quality objectives. However, at the same time vegetable crop residues are a vital link in closing the nutrient and organic matter cycle of soils. Appropriate and sustainable management is needed to harness the full potential of vegetable crop residues. Two fundamentally different crop residue management strategies to reduce N losses during winter in intensive vegetable rotations are reviewed, namely (i) on-field management options and modifications to crop rotations and (ii) removal of crop residues, followed by a useful and profitable application.

Keywords: vegetable crop residues; leaching; N-immobilizing materials; catch crops; intercropping; composting; anaerobic digestion; ensilage

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1. Introduction

Field vegetable production in Europe amounted to 376×10^3 hectare in 2012 leading to a total harvested production of nearly 10 G tons [1] (Table 1). As such, the vegetable cropping area is small compared to arable cropping, but it has a relatively large economic value in many member states due to the high added value of vegetables compared to arable crops. Because of this, vegetables are often grown on the most fertile soils and receive relatively large inputs of fertilizers and organic matter. Given the very intensive nature of the production systems in which vegetables are typically grown, vegetable cropping is often associated with low nutrient use efficiencies and large nutrient losses. One of the most significant issues with respect to nitrogen losses is the management of vegetable crop residues. Vegetable crop residues take a particular position relative to arable crops due to often large amounts of biomass with a high N content left behind on the field [2] (Table 2). An extensive overview of the total fresh matter and N content of vegetable crop residues has been given by Fink *et al.* 1998 [3]. Vegetable crop residues are characterized by narrow C:N ratios [4–7] and despite decreasing soil temperatures during autumn, high rates of N mineralization and nitrification still occur [8,9]. Furthermore, vegetable crops are often the last crop before winter in temperate maritime climates and several vegetable crops are harvested before they reach physiological maturity resulting in high N needs up to the time of harvest and thus often high residual soil mineral N, e.g., 100 kg N ha^{-1} at harvest of a cauliflower crop [10] and 125 kg N ha^{-1} at harvest of a leek crop [11]. The combination of these factors with net precipitation surplus in autumn and winter in temperate climates in Europe make intensive vegetable rotations particularly prone to N losses during winter. Nitrate leaching has been found to amount to 207 kg N ha^{-1} following a cabbage crop harvested in September on a sandy loam soil [12], 282 kg N ha^{-1} following a broccoli crop on a loamy soil harvested in November [13] and 293 kg NO_3^--N ha^{-1} following a cauliflower crop on a sandy loam soil harvested in October [14]. Furthermore, the combination of high soil mineral N content with high soil moisture promotes denitrification rates and increases N losses as N_2 through intermediates as NO and N_2O [15,16]. The latter is an important greenhouse gas with a global warming potential about 310 times as strong as CO_2 [17]. In a laboratory study conducted on a sandy soil at the moisture content at the time of sampling (125 g/kg soil) total N_2O emission from white cabbage, Brussels sprouts and broccoli ranged between 0.13 and 14.6% of the applied N in 11 weeks [18]. Field N_2O emissions following a cauliflower crop harvested in September on a silty clay loam in South Germany were found to range between 1.1% and 3.7% of the N content of the crop residues [19]. Any measurements of N_2 losses from soils are extremely challenging and costly and the magnitude of N_2 emissions related to vegetable crop residues remains largely unknown, but likely contributes significantly to N losses from agricultural systems [20,21]. In contrast, ammonia volatilization appears to be negligible when vegetable crop residues are incorporated [22,23].

Due to the high risk of N losses during winter vegetable crop residues pose a possible threat to maintaining water quality objectives, but at the same time are a vital link in closing the nutrient and organic matter cycle of soils. Appropriate and sustainable management is needed to obtain the full potential of vegetable crop residues while meeting water quality objectives set by the Nitrates and Water Framework Directive.

Table 1. Harvested production of open field vegetable crops in the European Union (EU) in 2012 [1].

Harvested Production [1000 ton]	EU	Climate Zones in the European Union		
		Atlantic	Mediterranean	Continental
Cauliflower & Broccoli	2249	1141	1064	44
White Cabbage	3557	2120	661	777
Celery	274	59	114	101
Leek	848	670	174	3
Lettuce	2320	895	1373	52
Spinach	514	317	196	1
Total	9761	5201	3582	978

Table 2. Fresh biomass and N content of vegetable crop residues.

Crop Residues	Fresh Matter (ton ha^{-1})	N Content (kg N ha^{-1})	Reference
Cabbage	NR	115	[11]
Cabbage	40–60	170–200	[24]
Cauliflower	NR	111	[25]
Cauliflower	30–50	150	[24]
Cauliflower	NR	193	[10]
Cauliflower	NR	92–128	[26]
Cauliflower	NR	110–200	[19]
Brussels Sprouts	NR	138	[11]
Brussels Sprouts	50–70	140–240	[27]
Broccoli	NR	76–304	[28]
Leek	NR	54	[11]
Celery	NR	25–60	[29]

NR = not reported.

1.1. Vegetable Crop Residue Composition

Probably the most important crop characteristic affecting N mineralization is the N content or the C:N ratio. The C:N ratio has been shown to be a good indicator of N mineralization rate [30,31]. In general incorporation of organic material with a C:N ratio greater than 20–40 results in net N immobilization [32–34]. Vegetable crop residues are characterized by C:N ratios ranging between 10 and 20 [4–7] and mineralize rapidly. During summer generally more than 80% of N present in cauliflower crop residues will be mineralized within eight weeks [35].

Beside C:N ratio other biochemical characteristics, such as hemicellulose, cellulose and lignin content, also influence microbial activity and N mineralization rate [35–37]. Different plant parts, *i.e.* stems, leaves and roots, show specific patterns of decomposition related to their biochemical composition. In general roots decompose more slowly than stems and leaves because of a higher lignin content and larger C:N ratio [32,36–38]. In a 36-week incubation experiment, maize leaves and stems were found to mineralize more rapidly than maize roots. This may be explained by higher amounts of carbohydrates and low molecular weight aliphatic compounds in the stems and leaves compared to the roots, which contain larger amounts of lignin, cutin and suberin [39]. Furthermore, interconnections between different cell wand components, such as pectic substances, hemicellulose and cellulose, should be taken into account when assessing crop residue mineralization [40–42]. Predictions based simply on the N content can thus be misleading [43,44] and the lignin:N ratio is hypothesized to be a better predictor of mineralization rates than C:N ratio [40,45,46]. However, vegetable crop residues generally have high N mineralization rates whatever measure of biochemical residue quality is used [47].

1.2. Contribution to Soil Quality

Incorporation of vegetable crop residues affects soil quality not only in terms of nutrient supply [48–51] but also by influencing soil food web organisms [52,53] and improving soil physicochemical properties, resulting in a better environment for crop growth and improved productivity [54,55]. Several studies have shown a positive impact of crop residues on soil nutrient pools [49,51,56,57]. Vegetable crop residues are an important link in the soil N cycle by releasing large amounts of N over short term periods [58] and, if this N is conserved in the soil, may contribute to the N supply for the succeeding crop [25,59–61]. In a comparison of fertilizer recommendation systems across Europe [62], fertilizer advice was sought for a cauliflower crop following another summer cauliflower crop. Soil mineral N content in the 0–90 cm soil layer following the first cauliflower crop was 296 kg N ha^{-1} and most systems taking into account soil mineral N content advised a zero N fertilizer rate, highlighting the important role of vegetable residues in nutrition of the subsequent crop. Fertilizer trials on a loam soil demonstrated a reduced N fertilizer need of 40 kg N ha^{-1} for spring barley succeeding vegetable crops (cauliflower, swede, bulb onion and peas) grown in the previous autumn. At an identical fertilizer rate the yield of spring barley increased by 0.71 ton ha^{-1} when succeeding a cauliflower crop compared to succeeding oats [25]. In addition to N, crop residues are also a source of other macro-and micronutrients [63–65]. To the best of our knowledge, no results concerning the contribution of vegetable crop residues for other macro- (P and K^+) or micronutrients (e.g., Mg^{2+}, Zn^{2+}) have been reported, and therefore we use data from arable crops as an indication of the potential. In a four-year field study on a silt loam soil, complete corn stover removal reduced available P by 40%, exchangeable Ca^{2+} and Mg^{2+} by 10%, and exchangeable K^+ by 15% [55], and a similar effect may be expected for vegetable crop residues. Higher levels of microbial C and N have been reported to be directly related to the presence of crop residues [52] that provide a direct C and nutrient source for soil organisms and mitigate soil temperature and moisture content fluctuations, which enhances soil biological activity [53,55].

Given the particular contribution of vegetable crop residues to N cycling and the potentially very large N losses, it is of vital importance to manage these residues in such a manner that N can be conserved maximally for a next crop. This review addresses the specific position of vegetable crop residues and evaluates two fundamentally different crop residue management strategies to reduce N losses during winter in intensive vegetable rotations, namely (i) on-field management options and modifications of crop rotations and (ii) removal of crop residues followed by a useful and profitable application. Whenever data are available, the management options are evaluated in terms of impact on soil quality, nutrient return to soil and N losses.

2. *In Situ* Management Options

2.1. Leave Crop Residues Intact on the Field

Rather than immediately incorporating vegetable crop residues following harvest in autumn, the crop residues could be left undisturbed, which slows down mineralization [59,66–68], and incorporation can be delayed to a period when risks of N losses through leaching or denitrification are lower (e.g., towards the end of winter) [69]. Crop residues of leek and broccoli have been found to contribute 20% to 60% to nitrate leaching below 90cm in a sandy soil. Leaving the crop residues of broccoli intact on the soil surface reduced nitrate leaching to 43% relative to incorporation, but no reduction in leaching was observed for the leek residues. In contrast to broccoli crop residues, decomposition of leek residues appeared not to be slowed down sufficiently by leaving the residues intact on the soil surface in order to reduce nitrate leaching [70]. However, ammonia volatilization could increase when leaving vegetable crop residues undisturbed on the field. Cumulative ammonia volatilization of leek residues remaining on the soil surface amounted to 10.8% of total N content after 119 days compared to 0.07% when leek residues were incorporated [22].

When harvesting of a vegetable crop is done in such manner that the rooting system of the crop residues remains intact (e.g., cauliflower crops for the vegetable processing industry), resprouting crop residues may act as a catch crop and take up N during autumn and winter. A four-year-study evaluated the influence on an organic crop rotation, relying on green manures and winter catch crops for soil fertility (no animal manure application), on soil mineral N content on a sandy loam soil. Among the winter catch crops were residues of white cabbage left to grow after harvest in October. Soil mineral N content averaged across all measurements was reduced by 39% compared to an identical crop rotation without winter catch crops and relying on manure input [71].

Research on leaving vegetable crop residues undisturbed is mostly scattered and covers only partial aspects of N losses during winter. A more systematic evaluation of the partitioning of N losses and of the overall N losses related to this management option, including the influence of meteorological conditions is needed to allow a complete assessment of this management option.

Many plant pathogens rely on crop residues as a host to survive between crops, and incorporation of infected crop residues is the common strategy to control such pathogens [72]. Hence, while postponed incorporation or non-incorporation of vegetable residues may aid in mitigating N leaching during winter, it may have adverse effects on disease control. Retaining crop residues on the soil surface may lead to a wetter and cooler soil environment due to reduced evaporation [73] and increased reflectivity [74]. Depending on the type of plant disease this changed microclimate may stimulate, mitigate or have no effect on the propagation of the disease or pathogen [75]. Similarly the retention of infested crop residues might increase plant pathogen numbers and infestation frequencies. Some studies report a decreased crop yield because of difficulties in planting of the succeeding crop through the residue mulch and poor stand establishment [76,77].

2.2. N-Immobilizing Materials

Co-incorporation of vegetable crop residues with other organic material may influence NO_3^--leaching either through N immobilization in microbial biomass of mineralized residue N or by reducing N mineralization rate of the residues [4,58,78]. Biochemical characteristics that promote N immobilization or decrease N mineralization include a high C:N ratio, a high lignin content and high polyphenol content [4,79]. Materials rich in C and low in N stimulate immobilization of soil mineral N through microbial uptake, whereas addition of materials high in lignin or polyphenol content slows down microbial decomposition of vegetable crop residues. Polyphenols have a twofold influence on the N mineralization and immobilization process. Polyphenols possess a strong affinity for amide groups and hence have a strong protein binding capacity [80,81]. Furthermore, they exert a direct toxic effect on soil microbial biomass hence suppressing N mineralization [82,83]. Materials, such as immature compost, straw, paper waste and saw dust, belong to these categories and have been shown to reduce N leaching under controlled conditions [47,79,84,85].

In a field experiment established on a silt loam soil cauliflower, leaves (50 ton ha^{-1}) and stems and roots (23 ton ha^{-1}) were incorporated with straw, green waste compost or saw dust (at an amount equivalent to 5 ton C ha^{-1}). Co-incorporation of straw, green waste compost and saw dust reduced N leaching by 27%, 24% and 18%, respectively, compared to incorporation of only cauliflower residues [4]. Similarly co-incorporation of sugar beet foliage (42 ton fresh matter ha^{-1}) with compacter waste (3.6 ton C ha^{-1}) provided by the cardboard industry reduced leaching by on third compared to incorporation without compacter waste [78]. Co-incorporation of vegetable crop residues with N-immobilizing materials has also been found to reduce N_2O emissions [5,78,79]. Celery residues were mixed and incorporated with N immobilizing materials in a sandy soil at 15 °C and 80% water filled pore space. Straw, green waste compost, and saw dust were found to reduce N_2O emission by 60%, 55% and 53%, respectively, compared to a celery only treatment [5]. The N immobilization potential of immobilizing materials has been found to be higher under optimal lab conditions (ground residues, 15 °C) than in field conditions [4,86]. Soil mineral N content in autumn of identical crop rotations did not differ when spelt straw was harvested or left on the field without incorporation [87]. Hence homogeneous mixing of vegetable crop residues with N-immobilizing materials appears necessary to ensure contact between decomposing microorganisms and both organic materials. Additionally sufficiently high soil temperatures have been shown to be vital to allow decomposition of recalcitrant molecules [88,89], which is needed to obtain the full N immobilizing potential. Further fine-tuning concerning the potential material, set-up and manner of application is needed via field experiments to reduce N losses during winter while not compromising crop yield of a succeeding crop [78]. One drawback concerning the use of N-immobilizing materials is the large amounts of immobilizing materials needed. For an effective and significant immobilization, the equivalent of 5–10 tons of C needs to be incorporated. Given the high price of some of these materials, the limited availability, and the logistical problems related to transport and application, the economic and practical feasibility of this option remains doubtful.

Immobilization of N from vegetable crop residues should be followed by timely remineralization, *i.e.* at the time the next crop needs the N. Research has been performed to stimulate remineralization of N immobilized in microbial biomass to release N during the next growing season [58]. In a laboratory study celery residues were mixed with immobilizing materials at an equivalent rate of, respectively, 36 ton fresh matter ha^{-1} and 2.5 ton C ha^{-1} and incorporated in a sandy loam soil. Ninety-nine days after the start of the incubation a "remineralizer" was added (molasses at 3 ton C ha^{-1}, or vinasses, malting sludge or dairy sludge at 1.5 ton C ha^{-1}. Vinasses caused a remineralization of 232 kg N ha^{-1} from day

42 to day 70 after its application, but effects of the other remineralizers were limited and short-lived [86]. Likewise in a field experiment no remineralization was observed after addition of dairy sludge or vinasses in March at a rate of 1 ton C ha^{-1} to a silt loam soil following autumn incorporation of cauliflower crop residues with straw, green waste compost, saw dust or paper sludge [4]. Incorporation of sugar beet residues with molasses at a rate of 3.7 ton C ha^{-1} in a Chromic luvisol soil in October increased soil mineral N content by 47 kg N ha^{-1} after six months compared to incorporation of only sugar beet residues [78]. The N in the sugar beet residues had not been immobilized in microbial biomass by addition of N immobilization materials, which may explain the significant effect of the molasses contrary to earlier described laboratory and field experiments [4,86].

2.3. Winter Catch Crops

Inclusion of catch crops in vegetable crop rotations may help to prevent nitrate leaching during winter [90,91] and may positively influence soil quality, microbial activity and reduce soil erosion [92–95]. However, the efficiency of catch crops to retain N depends on many factors including type of catch crop, sowing and harvesting dates and soil tillage [10,90,96]. Of all factors influencing catch crop efficiency, the sowing time is undoubtedly the most decisive. In general, the assessment of the impact of varying plant, soil and management factors on catch crop efficiency has focused on cereal and arable crop rotations and much less on vegetable rotations. However, results from studies of catch crops following cereal and arable crops may also be used to assess the potential impact of catch crop use in vegetable crop rotations.

While catch crops sown in summer have been found to be able to reduce N losses during winter significantly [97–100], a variable or limited effect has been observed in other studies [10,101]. The effect on nitrate leaching of forage rape sown late August after spring wheat on a sandy soil varied between −25% and −72% compared to leaving the soil fallow during winter during a three-year experiment [101]. Time of sowing has a crucial impact on catch crop efficiency and generally catch crop growth and performance decrease rapidly when postponing the sowing date [97,102]. The decrease of daily N uptake has been estimated at 2 kg N ha^{-1} [103] to 3.4 kg N ha^{-1} [104] for each day of delay of planting of a catch crop in August until September in temperate climate zones. Accumulated N in aboveground biomass of winter rye in autumn decreased from 41 kg N ha^{-1} to 8 kg N ha^{-1} when sown in early September and early November, respectively [105,106]. Generally a rapid decrease of N uptake can be observed for catch crops grown before or after September (Figure 1). Aboveground N content of a catch crop is only part of the catch crop total N uptake but its assessment allows an evaluation of the catch crop development and performance. Reported positive effects of catch crops on nitrate leaching during winter are variable (e.g., due to differences in precipitation), but show a similar decreasing trend when postponing the sowing date of the catch crop (Figure 2). Unfavorable growing conditions or high precipitation before full establishment of the winter catch crop strongly influence catch crop performance in a negative manner [101,107,108]. Hence the use of catch crops as a management option to reduce nitrate leaching in conventional vegetable crop rotations in temperate climates seems limited to vegetable crops harvested in summer or early autumn. Because a considerable amount of vegetable crops are harvested later than September, alternative management options will certainly be needed to mitigate N losses during winter.

Figure 1. Effect of sowing date on the aboveground N uptake by catch crops measured in autumn [97,105–107,109–111].

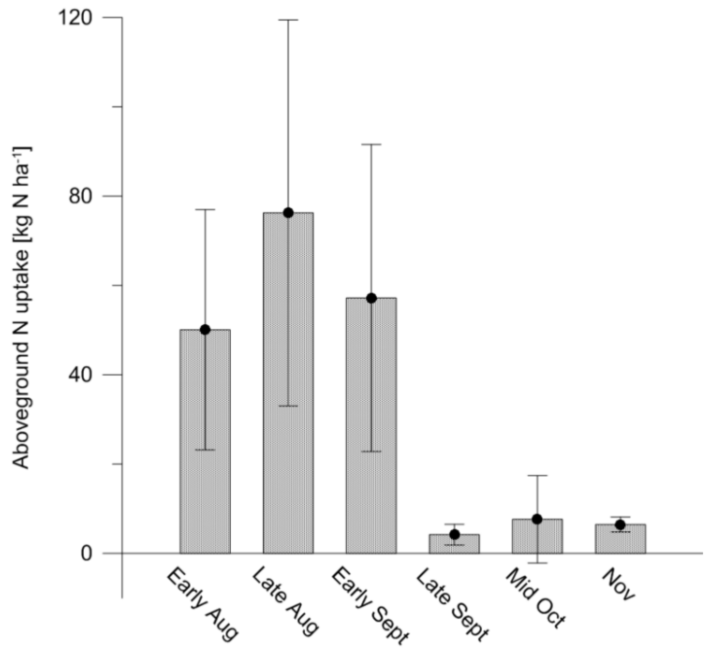
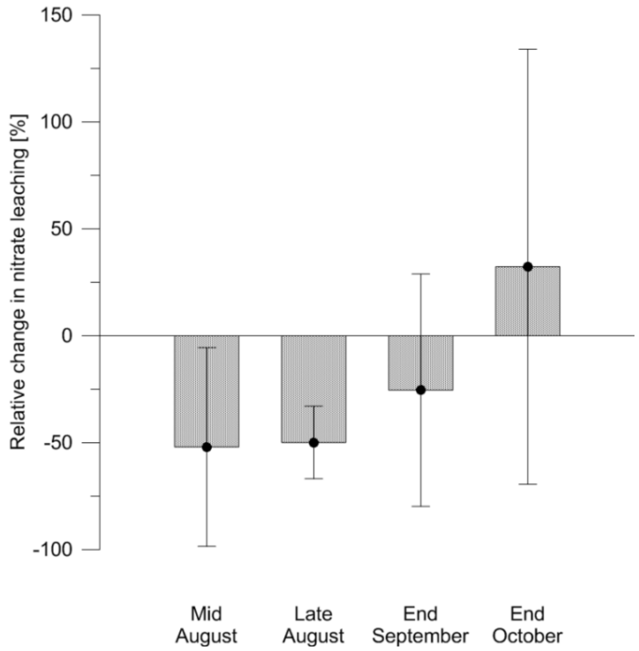


Figure 2. Effect of sowing date of catch crops on nitrate leaching during winter relative to no catch crop sowing [97,101,109,110,112].



Preferably, catch crops sown after harvest of a vegetable crop in autumn should have following features:

- Fast developing rooting system: temperate climates in Europe are often characterized by high precipitation and rapid leaching of nitrate. Rapid root growth may mitigate downward movement of nitrogen to deeper soil layers (e.g., Italian ryegrass, oats).

- Deep rooting system: many vegetable crops have a shallow rooting system (e.g., cauliflower, leek) and are incapable to take up N from deeper soil layers. The rooting system of crucifers grows deeper than roots of cereals and allows scavenging of nitrates from deep soil layers [113].
- Winter hardiness: the catch crops should be able to survive frost to avoid N losses from catch crop biomass (e.g., winter rye, Italian ryegrass, triticale).

2.4. Intercropping of Catch Crops

When catch crops are sown after harvest of the vegetable crop there is a time lag between crop harvest and effective N uptake by the catch crop, resulting in a higher risk of nitrate leaching and poorer germination circumstances for the catch crop. Intercropping allows establishment of catch crops before the harvest of the vegetable crop and may forestall N losses during autumn and winter. Furthermore, no extra tillage operation is required in autumn, thus avoiding additional N mineralization [114]. However, intercropping of a catch crop increases the total N demand and may cause considerable competition for water and nutrients between the main crop and the intercropped catch crop. Appropriate intercropping strategies including complementarity in rooting systems, adapted spatial field design and specific measures (e.g., root pruning, time of undersowing) are necessary to maintain vegetable crop yield [71]. Intercropping of chicory in a leek crop allowed to strongly deplete soil nitrate content below the chicory (0–2 mg NO_3^--N kg^{-1} dry soil) and leek row (2–4 mg NO_3^--N kg^{-1} dry soil) without reducing vegetable yield per m crop row nor quality. To reduce competition between both crops leek was planted at 0.5 m and 0.75 m row distances with the chicory grown in the 0.75 m interrow spacing [115]. Similarly intercrops (red clover, birdsfoot, trefoil, salad burnet and winter rye) were sown in 0.2 m rows alternating with 0.5 m stripes of bare soil into which white cabbage was planted the next year. Root pruning of the intercrop was necessary to increase the competitive ability for N uptake of the white cabbage relative to the intercrops and mitigate lower cabbage crop yields [116]. The combination of root pruning, adapted field set-up and early establishment of intercropped green manures in an organic vegetable rotation allowed to achieve similar vegetable crop yields while reducing soil mineral N content by 44% on average compared to the conventional organic vegetable rotation [71]. When part of the land area destined for vegetable cultivation has to be redesigned to allocate intercrops this management option can only be economically feasible when the area available for vegetable cultivation can be expanded [71] or if the intercrop could has value as a cash crop [117].

3. Removal of Vegetable Crop Residues

Removal of crop residues can be viewed as a very drastic measure to substantially reduce N losses [118]. Furthermore, an improved synchronization of crop nutrient demand and nutrient availability may be achieved by removal and subsequent timely reapplication of vegetable crop residues [87]. Removal of 20% of cauliflower residues after harvest reduced nitrate leaching by 8% on a sandy soil [119] and it may be expected that higher removal rates further lowers N losses during winter (Table 3). To the best of our knowledge all studies assessing the impact of crop residues removal on soil quality concern arable crops, often destined to evaluate the feasibility of a biobased energy production. However, results of removal of arable crop residues may be used as an estimate of the potential impact of vegetable crop residues removal.

Table 3. Relative reduction in nitrate leaching (Δ leaching), N balance (ΔN balance) or soil mineral N content (Δ Soil N_{min}) as a consequence of alternative management options in intensive vegetable rotations compared to conventional practice (incorporation of crop residues; no winter catch crop or intercrop).

Method	Main Crop	Specifics	Soil Texture	Δ N Leaching %	Δ N Balance %	Δ Soil N_{min} %	Reference
Crop Residue Removal	Cauliflower	20% removal	Loamy sand	−8	−76		[119]
	Broccoli	Contribution of the crop residues to total N leaching	Sand	−35 to −60			[70]
	Leek	Contribution of the crop residues to total N leaching	Sand	−20 to −35			[70]
No Incorporation	Broccoli	Leave crop residue on the soil surface	Sand	−15 to −20			[70]
	Leek	Leave crop residue on the soil surface	Sand	0 to +15			[70]
N-Immobilizing Materials	Cauliflower	Green waste compost at 5 Mg C ha^{-1}	Sandy loam	−27			[4]
	Cauliflower	Wheat straw at 5 Mg C ha^{-1}	Sandy loam	−24			[4]
	Cauliflower	Sawdust at 5 Mg C ha^{-1}	Sandy loam	−18			[4]
	Cauliflower	Compacter waste at 3.6 Mg C ha^{-1}	Sandy loam	−30			[78]
Winter Catch Crops	Cauliflower	Fodder radish	Sand, sandy clay loam, silty loam		−14		[10]
	Cauliflower	Sudangrass	Sand, sandy clay loam, silty loam		−8		[10]
	Sugar beet *	Radish	Silt	−59			[120]
	Sugar beet *	Winter rye	Sandy loam	−40			[101]
Intercropping	Leek	Chicory in interrow spacing of 0.75 m	Sandy loam			−50	[115]
	Carrots, onion, Lettuce, white cabbage	Winter rye, green manure	Sandy loam			−44	[71]

* When considering an entire winter period sugar beet residues result in an important net N mineralization [121].

Inappropriate removal of crop residues may have adverse effects on soil quality, crop production and environment but the impact of residue removal is site specific and dependent of soil texture, nutrient status, slope, climatic conditions, management practices and rate of removal [122–124]. Effects of crop residue removal on crop yield and soil properties are sometimes conflicting, which makes determination of the influence of crop residue removal difficult [55,125]. However, decrease of SOM and N content appears to be consistent and rapid even with small removal rates [126–129]. Depending on the initial soil N and P status a decrease of soil nutrient pools due to crop residue removal may bring about an increased demand for additional N, P and K fertilizers in order to maintain soil fertility [49]. Hence for those soils where vegetable crop residues are removed, an appropriate crop residue removal rate should be determined based on the minimum level of crop residue that must be kept on land to maintain the soil quality and if necessary best available techniques should be applied to mitigate unfavorable effects of residue removal [127].

Crop residue removal is a common practice for cereal crops whereas residues of most vegetable crops are normally left on the field whether or not followed by incorporation. Harvest machines are currently not designed to efficiently collect vegetable crop residues and should be adjusted to render residue removal feasible. Furthermore, many vegetable crops are harvested in late autumn in adverse weather and soil conditions, and harvest of some crops may take place in several stages (e.g., fresh market cauliflower). Additional on-field operations and machinery required to remove vegetable crop residues may hence cause serious soil compaction. In a 3-year experiment on a silt loam soil the effect on an artificially induced compaction layer starting at 10cm on crop yield of cabbage (*Brassica oleracea* L. capitata group), cucumber (*Cucumis sativus* L.), snap bean (*Phaseolus vulgaris* L.), and sweet corn (*Zea mays* L.) was examined. The average reduction in total marketable yield was 73%, 49%, 41% and 34% for cabbage, snap bean, cucumber and sweet corn, respectively [130]. Furthermore, the formation of waterlogged or anoxic zones due to soil compaction may lead to increased denitrification and hence loss of N [131,132]. In experiments performed on potato fields, highest N_2O emissions were measured from tractor-compacted soil [133]. Climate, soil conditions and crop specifications will strongly influence the feasibility of removal of the considered crop residues. Some vegetable crop residues, such as leek leaves following leek cleaning and preparation, are already removed from the field and could profit from a useful and profitable application in order to valorize and make best use of these valuable organic materials.

4. Valorization of Vegetable Crop Residues

Vegetable crop residues, removed after harvest can be processed and stored in a stabilized form to be reapplied to the field at the end of winter when there is much less risk of N losses. A complete or partial return of the organic matter and nutrients present in the removed crop residues aids in maintaining soil carbon and nutrient stocks and may mitigate negative effects caused by crop residues removal [134,135]. The crop residues may be used for further valorization purposes, such as composting, fodder or bioenergy production. In the latter case, the digestate may also be returned to the field.

4.1. Composting

4.1.1. N Losses Related to Composting

In Belgium vegetable, fruit and garden waste (VFG) of households are collected selectively and composted. The chemical properties of VFG compost may be used as a first indication of the properties of compost of vegetable crop residues (Table 4). However, the properties and quality of the end product of the composting process will vary due to variation in feedstock materials, set-up and process conditions. Vegetable crop residues are characterized by a high moisture content and small C:N ratio (Table 2). Addition of structural material, such as bark or wood chips, is required to start and maintain the composting process and minimize N losses during composting [136–138]. These losses have been found to amount to 4%–6% and 10%–17% for a broccoli and leek compost pile, respectively, mixed with straw and wood chips in a 1:1 vegetable crop residue: structural material mass ratio [136]. Doubling the amount of structural material reduced N losses from 16% to 8% from compost piles consisting of leek residues and green waste compost. These losses occurred mainly as gaseous losses since N losses via percolating water were found to be negligible [139].

Table 4. Average composition of vegetable, fruit and garden (VFG) compost, digestate without post treatment, ensilaged vegetable crop residues and fresh vegetable crop residues.

Parameter		**VFG Compost**	**Digestate**	**Silage**	**Fresh Vegetable Crop Residues**
DM	%/FM	70.1–71.9	1.5–13.5	16.1–19.2	8.3–22.1
OM	%/DM	39.1–39.2	63.8–75	83.7–90.7	38–76
Total N	%/DM	1.9–2.1	3.1–14	2.2–2.8	0.9–3.9
NH_4-N/Total N	%/ total N	16	44–81	16–31	NR
C:N		10.2–10.9	3.5–8.5	19–23	10–25
N:P		4.2–4.7	5–8	NR	3.3–12.5
Total P	%/DM	0.5	0.6–1.7	NR	NR
pH		NR	7.3–9.0	3.59–4.27	NR
References		[140,141]	[142]	[143]	[3,4,9,32]

FM = fresh matter, DM = dry matter, OM = organic matter, NR = not reported.

4.1.2. Contribution to Soil Quality

Several positive effects are attributed to compost amendment of soil. Compost was shown to (i) protect against soil erosion [144]; (ii) improve soil physical properties, such as available water content [145,146] and aggregate stability [147], and (iii) increase soil organic matter and nutrient content [144,146,148–150]. Experience concerning the use of compost of vegetable crop residues is limited. A long term field trial set up on a loamy soil in Flanders, Belgium assessed the effect of vegetable, fruit and garden waste (VFG) compost application on soil carbon content and nitrogen supply capacity. Compost was applied triennial, bi-annual or yearly at a rate of 15, 30 and 45 t ha^{-1}. Soil carbon content increased with increasing frequency and amount of compost application. A gradual increase of mineral N stock in spring was observed over the years, which may be explained by an increased N mineralization potential [151]. A positive effect of compost amendment on crop yield may be expected to take place in the longer term due to a combination of slow N release and higher soil quality [149,152,153]. Yearly N recovery rate of VFG compost varied between 4.5% and 21.7% [151], which is in agreement with values reported for compost of municipal waste or manure [154,155].

When reapplying compost of vegetable crop residues to the field not only C and nutrients present in the vegetable crop residues are reapplied in a stabilized from but also the C and nutrients of the added structural materials. N release from composted vegetable crop residues takes place over several years [156] as opposed to the very rapid mineralization of fresh vegetable crop residues [7]. This release may be quantified and should be taken into account when defining N fertilizer recommendation in order to avoid N losses. Furthermore, reapplication of composted crop residues during spring allows to improve synchronization between N apply and demand.

4.2. Anaerobic Co-Digestion

4.2.1. N Losses Related to Anaerobic Digestion

Vegetable wastes tend to have high moisture contents, high organic carbon contents and are highly biodegradable in an anaerobic digester [157,158]. These properties enhance a rapid hydrolysis, which may lead to acidification of the digester and the consequent inhibition of methanogenesis [159]. Co-digestion with other feedstocks, addition of trace elements [158] or use of a two-phase digester may be needed to ensure stable performance [160]. Bioreactor performance of anaerobic digestion of fruit and vegetables has been evaluated [160–162] but the composition of the produced digestates remained undiscussed. An overview of digestate characteristics of manure anaerobic digestion has been given by Möller and Müller (2012) and may be used as a first indication of the properties of digestate of vegetable crop residues (Table 4). However, depending on the raw materials and process characteristics digestate composition may vary greatly. No nutrients are lost during anaerobic digestion but the composition and nutrient availability of the digested product may differ from the feedstock [142]. Anaerobic digestion converts organically bound N to ammonia and enhances plant N availability, which has been found to be similar to that of digested cattle slurry [163]. Hence reapplication of digested vegetable crop residues would lead to an increased plant N availability during the first year, but a lower residual effect in the years after application [164]. Given the high ammonium content of digestates an adequate adjustment of the timing, amount and mode of application of additional N fertilization should be made to avoid leaching and ammonia volatilization [87,165]. However, balancing N_2O-emissions over a whole cropping system showed a 38% decrease for harvest, anaerobic digestion and reapplication of spring pea crop residues and cover/grass-ley within the same cropping system compared to mulching and incorporation of the biomass as a green manure [87]. The lower organic matter content and biological oxygen demand of digestates [166] leading to less anoxic microsites might explain the lower N_2O emissions.

4.2.2. Energetic Valorization

Furthermore, anaerobic digestion valorizes the energy value of crop residues and provides a renewable energy source that doesn't compete with food production for land usage. The possible energy yield will be determined by the biomass yield and biomass convertibility to methane. The methane potential has been investigated for different crops with an emphasis on cereals and grasses [167]. The methane production potential of vegetable crop residues has been found to range between 0.190 ± 0.009 m^3 CH_4 kg^{-1} volatile solids to 0.309 ± 0.013 m^3 CH_4 kg^{-1} volatile solids for leaves of cauliflower and headed cabbage, respectively [168]. For comparison, the methane potential of slaughter facility sludge, pig manure and dairy cattle manure amounts to 0.60, 0.356 and 0.148 m^3 CH_4 kg volatile solids^{-1}, respectively [169,170]. When performed under thermophilic condition (55 °C) anaerobic digestion reduces pathogens and weeds [171–173] and might improve the phytosanitary hygiene compared to leaving crop residues undisturbed on the field.

4.3. Ensilage

Ensilage is a simple and low-cost strategy to enable long-term conservation and valorization of vegetable crop residues. Ensilaged vegetable crop residues may be reapplied to the field in order to close nutrient cycles and maintain soil fertility [174] or used as feeding supplement for livestock [143]. Ensilage changes the chemical nature of the feed and can render some previously unpalatable products useful to livestock [175] and has been found to increase the methane potential (m^3 CH_4 kg^{-1} *vs* added) of sugar beet tops by 6%. However, a negative effect has been observed for cauliflower and white cabbage residues, with methane potential decreasing by 3% and 10%, respectively [176].

Ensilaged material should contain between 20% and 50% moisture for a sufficient compressibility in order to eliminate air. These moisture contents can easily be met with vegetable crop residues [177]. However, excessive moisture of more than 75% leads to an undesirable fermentation in later phases and produces sour silage [175,178]. The silage fermentation quality of vegetable crop residues (white cabbage, Chinese cabbage, red cabbage, and lettuce) was evaluated in small-scale fermentation systems and a high digestibility and a high NH_4^+-N content was found for all vegetable residue silages [143]. Similarly as for composting or anaerobic digestion, mixing of the vegetable crop residues with structural materials, such as straw, may help to mitigate N losses during ensilage.

To the best of our knowledge no research concerning field application of ensiled vegetable crop residues has yet been performed. Ensiled vegetable crop residues contained more NH_4^+-N than the starting materials [143] and may hence be a source of easily available N for crops during spring. However, N leaching risk may increase when the ensiled residues are applied during periods of low N crop demand. To fully assess the potential of removal, ensilage and reapplication of vegetable crop residues as possible management strategy, additional research concerning the influence of ensiled residues on C and N mineralization is needed.

4.4. Potential Bottlenecks for Removal and Valorization

Vegetable crop residues as a possible substrate for bio-energy production or feed have the advantage of being present in large amounts while the direct costs to produce them are often low. However, additional costs related to harvest and transport of vegetable crop residues may be considerable. A matter of concern is the large amount of soil removed together with the crop residues, which very seriously compromises subsequent processing and brings along additional costs. Crop residues are only seasonally available and storage of crop residues may be needed to ensure continuous operation of the digester. Ensilage could be used as a possible storage technique for vegetable crop residues before composting or anaerobic digestion.

N losses during processing or application of the processed crop residues should be minimized in order to reduce total N losses rather than shifting the pathways for N losses by removing the vegetable crop residues from the field. Addition of structural material and adequate coverage during composting [137] and adequate application techniques to mitigate ammonia volatilization when applying digestates [179] appear to be the most necessary measures. A certain degree of organic matter stability of the processed vegetable crop residues is required in order to avoid detrimental effects on the plant-soil system. Application of unstable and easily biodegradable materials prior to sowing or planting promotes microbial activity resulting in immobilization of inorganic N and thus loss of N-fertilizer value [165].

5. Conclusions

Soil texture and meteorological conditions have a strong influence on nitrate leaching, N_2O and NH_3 emissions and direct comparison of vegetable crop residue management options on N losses during winter should be made with care. Ideally evaluation of different management options would have to be grouped in inclusive long-term field experiments. While many studies focus on N leaching, the assessment of gaseous N emissions is equally important to obtain a complete overview of all N losses related to a specific management option and avoid pollution swapping. Mitigation of total N losses during winter might allow to reduce N fertilization need for the succeeding crop in spring but quantitative estimations remain lacking. Most research concerning the impact of crop residue removal on soil quality has focused on arable crop and only a few studies related to vegetable crop residues have been performed. To fully evaluate the feasibility of removal of vegetable crop residues as a measure to reduce nitrate leaching without jeopardizing future crop yields additional research is required. Bottlenecks here are the possible implications for soil physical quality (compaction) and the large amounts of soil removed with the crop residues. Some vegetable crop residues (e.g., leek leaves) are already removed from the field but remain to date often unutilized. Valorization (e.g., composting, anaerobic digestion, ensilage) could be used to conserve and upgrade this valuable organic material. Fine-tuning of these valorization processes, pre-treatments, required materials, is needed to obtain a high-quality material, which may be returned to the field on a suitable moment to maintain soil organic matter and nutrient reserves and maximize synchronization between N availability and demand. Additional knowledge concerning the impact of a complete or partial return of the (processed) vegetable crop residues to the field on soil organic matter and nutrient pools is required to assess the sustainability of the removal and valorization strategies.

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Author Contributions

Laura Agneessens, Jeroen De Waele and Stefaan De Neve analyzed data available from the existing literature. Laura Agneessens wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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