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Review article

The potential influence of plant-based feed supplements on sperm quantity and quality in livestock: A review

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ABSTRACT

The reproductive performance of male livestock is of economic importance, and improving semen quantity and quality, especially for artificial insemination, additionally helps to avoid the loss of valuable genotypes. The review focuses on the impact of oxidative stress on sperm production and quality in livestock, and the potential role of plant based anti-oxidants to control this impact. From scientific reports dealing with livestock, the paper compiles evidence on effective dietary measures affecting sperm production and quality. Where little or no data are available on livestock, it refers to sources regarding other mammals, including man. The review concentrates on the use of distinct plants as feed supplements rather than on ways to treat deficiencies and imbalances in energy or macro- and micronutrients. Feeding of maca (*Lepidium meyenii*) and khat (*Catha edulis*) has been shown to positively affect sperm production and quality in animals. Some evidence points to favourable effects of leucaena (*Leucaena leucocephala* and *Leucaena pallida*), sesbania (*Sesbania sesban*), pomegranate (*Punica granatum*), tomato (*Solanum lycopersicum*) and amaranth (*Amaranthus hypochondriacus*) as well, but studies are either superficial or results are partially contradictory. Finally, the review considers the potential usefulness of medicinal herbs. The list of such plants includes Chinese herbs such as *Lycium barbarum*, *Astralagus membranaceus*, *Acanthopanacis senticosi*, *Magnolia officinalis*, *Cornus officinalis and Psoralea corylifolia* and the Indonesian plant *Eurycoma longifolia*. European candidate plants are *Tribulus terrestris* and *Pendulum murex*. Future research should include the screening of other plants, concentrating on the large number of plants rich in metabolites because of their presumed effectiveness. The modes of action often require clarification for the plants with demonstrated effects.

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1. Introduction

The search for improvements in semen quality and, thereby, pregnancy rates using feed supplementation has obtained much less interest in application to male livestock than to female ones. This probably has economic reasons since a far higher proportion of the reproducing population is female, especially since the establishment of artificial insemination. However, customer satisfaction with artificial insemination centres and the profitability of semen processing in these centres depends also on the bulls' semen production. Removing males with insufficient sperm number or capability to fertilise from herds or from commercial semen production is costly and often results in the loss of interesting genotypes and animals with high breeding value. Kastelic and Thundathil (2008) stated that, in an unselected population, 20–40% of bulls are likely to have a reduced fertility due to impaired semen quality. In the case of artificial insemination, animals of special interest for improvements are those which high genetic merit and with semen quality parameters which are inferior but still close to the standards set by the artificial insemination centres. Feed supplementation might find its successful implementation in the treatment of these male animals rather than in trying to cure grossly abnormal semen. Developing countries may provide another field of application as in these areas many of the plants described later can be cultivated. Together with the often concomitantly low fertility status as a result of massive under- and malnutrition (shown by Mekasha et al., 2008 for Ogaden bucks), this provides a lot of room for improvement.

Nutritional status is of primary importance in determining semen quantity and quality (Brown, 1994; Robinson, 1996; Petherick, 2005; Robinson et al., 2006; Martin et al., 2010). Other influential environmental factors are climate, stress, pollution, management, genetics, and behavioural factors like experience and temperament (*e.g.*, Petherick, 2005; Mukhopadhyay et al., 2011). In adult animals, the effects of under-nutrition, with one or more nutrients or energy, malnutrition and nutrient imbalances, include reduced androgen secretion and low semen quality (Brown, 1994; Petherick, 2005). Approaches to feed supplements would consist of complementing animal diets with the lacking nutrient or energy, removing the imbalances, or both (Brown, 1994; Almeida et al., 2007). This would be especially important in developing countries (Martin et al., 2010). Such improvements would help to avoid classical cases of nutritionally caused, but often reversible, sub- or infertility. The nutrition-based strategies discussed in this review involve supplements containing ingredients with a direct effect on reproductive traits and aim, specifically, to improve sperm numbers and quality of animals that are well nourished in terms of macronutrients. Although general nutrition is very relevant, especially in developing countries, the present article thus focuses on targeted supplementation, an area where much less is known. This review does not consider experimental evidence for the efficiency of supplements in improving libido and the ability to serve, which are equally important properties for male fertility. Natural products with presumed or demonstrated effects on erectile-dysfunction or aphrodisiac activity in both human and animal males are numerous and have been reviewed previously (*e.g.*, Drewes et al., 2003). Even though the intention of this review is to focus on livestock, research performed on laboratory animals and humans is included where little or no research on livestock was available to support potential effectiveness.

2. Oxidative stress, related nutritional factors, and sperm quality

Reactive oxygen species (ROS; free radicals) are molecules that contain one or more unpaired electrons and are, consequently, very reactive, particularly with respect to lipids. They are produced at different sites in the mammalian body. In the mitochondria, the production of superoxide is a by-product of the respiratory chain (Balaban et al., 2005). In the testes ROS are produced during the normal testicular spermatogenesis and steroidogenesis (Mathur and D'Cruz, 2011). The sources of ROS produced by the sperm, especially the damaged ones, include radicals like hydroxyl ions, superoxide, nitric oxide, peroxyls and others (Makker et al., 2009). A certain, still low, concentration of ROS is necessary for the sperm function like capacitation, hyperactivation, acrosome integrity and sperm–oocyte fusion (Awda et al., 2009), but ROS become detrimental at excessive amounts. The sperm is very sensitive to lipid peroxidation because its plasma membrane is rich in polyunsaturated fatty acids (PUFA), especially in the long-chain PUFA docosahexaenoic acid and docosapentaenoic acid (Brinsko et al., 2005). The concentration of these PUFA decreases with age in bulls (Robinson et al., 2006) and the effect of PUFA supplementation is often positive, especially in older animals. However, the variability of its effects on semen characteristics of different mammals is astonishingly high (Rooke et al., 2001; Brinsko et al., 2005; Aitken et al., 2006; Robinson et al., 2006; Samadian et al., 2010). When applied in ruminants, PUFA may be efficient only when provided either in rumen-protected form or at very high levels in order to counteract their extensive ruminal biohydrogenation. Generally, the ideal supplementation levels are within a narrow range because PUFA at the same time stimulate the formation of ROS and are precursors of them (Aitken et al., 2006). Further factors increasing the concentration of ROS in the sperm are various mechanisms present in the sperm itself which are particularly active in defective sperms, and the presence of leukocytospermia (Aitken, 1995; Agarwal et al., 2003). Environmental toxins were shown to provoke an imbalance between antioxidants and ROS (Mathur and D'Cruz, 2011).

Sperm function is undisturbed when the levels of ROS and antioxidants are balanced, as this ensures that no significant damage will occur. In the case of metabolic oxidative stress, however, provoked by excessive ROS production or low antioxidant status or both, impaired sperm function may occur (Agarwal et al., 2003; Aitken and Baker, 2006; Makker et al., 2009). In addition, DNA fragmentation in both nuclear and mitochondrial genomes is a consequence of oxidative stress (Agarwal et al., 2003; Aitken and Baker, 2006). The defence mechanism of the sperm consists of three different and interdependent antioxidant protection systems (Makker et al., 2009), which are dietary (external), enzymatic or non-enzymatic (metabolic).

Dietary antioxidants include ascorbic acid (vitamin C), α-tocopherol (the major form of vitamin E), β-carotenes, carotenoids, flavonoids, and retinol (vitamin A). Various studies have investigated their respective roles in determining semen characteristics, as well as the effects of their respective deficiencies or supplementations or both (Smith and Akinbamijo, 2000; Rao and Sharma, 2001; Castellini et al., 2002, 2007; El-Demerdash et al., 2004; Song et al., 2006). Feeding recommendations, therefore, include vitamins, and currently there is a tendency to use supra-nutritional doses – supplementation clearly beyond known requirements – in order to provoke a pharmacology type of effect in male reproducing livestock. Notwithstanding, Castellini et al. (2002) demonstrated that supra-nutritional vitamin E administration to fertile rabbits improves the oxidative stability of the sperm but not motion characteristics and fertilising ability of the sperm, in spite of the higher vitamin E concentrations occurring in the semen.

Superoxide dismutase (SOD), catalase, and the glutathion-peroxidase-reductase system form the complex of the enzymatic antioxidants. The SOD converts superoxide to hydrogen peroxide that catalase subsequently converts to oxygen and water (Aitken and Baker, 2006). Zinc, copper, and manganese are components of SOD. Selenium is a cofactor of glutathione peroxidase (GP × 1–8), the enzyme that catalyses the degradation of peroxides, and part of the selenoprotein P. Their respective roles were reviewed by Flohé (2007). The effects of deficiency or supplementation or both of these minerals and trace elements on sperm characteristics have been intensively investigated (Kendall et al., 2000; Smith and Akinbamijo, 2000; Colagar et al., 2009; Martin et al., 2010). This knowledge of the importance of distinct minerals and trace elements for semen quality has increased their inclusion in feeding recommendations and their adoption in designing tailor-made mineral supplements for breeding males. Still, there may be many unknown interactions and regular refinement of feeding practices is indicated. Supra-nutritional doses of Zn, Co, and Se were found to enhance the production of motile sperm with intact membranes (Kendall et al., 2000), but thresholds of detrimental levels are widely unexplored.

Non-enzymatic antioxidants are represented by urate, pyruvate, glutathione, ubiquitol, taurin, hypotaurin, and the metal-binding proteins albumin, ceruloplasmin, metallothionein, transferrin and ferritin (Taylor, 2001).

Plant-based feed supplements, which are rich in certain elements or compounds, may provide substances that act as antioxidants in metabolism, either directly or indirectly, by activating one of the mechanisms described. They would help to improve sperm quality, at least in stressful situations where the sperm's own countermeasures are no longer sufficient.

3. Enhancement of sperm quantity and quality with plants rich in effective secondary metabolites

Plants with beneficial effects on health (nutriceuticals) are receiving increasing attention both in the public forum and in the scientific community. However, even though there are many claims of positive effects on semen quality, very few of them have been subjected to rigorous scientific investigations. Nevertheless, increasing bodies of evidence are developing for some plants, while the promising effects of others can be deducted only from indirect indications.

3.1. Lepidium meyenii *Walpers (maca)*

Maca is a traditional Andean crop of the Brassicaceae family that grows best at altitudes between 3500 and 4500 m a.s.l. in the Peruvian Highlands. Maca is primarily cultivated for its hypocotyls, which were first demonstrated to improve libido (Zheng et al., 2000). No peer-reviewed publications on the sperm quantity or quality enhancing properties of maca are available before 2001. However, an experiment reported in a Master thesis from Peru (Matos, 1995, cited in Hermann and Bernet, 2009) showed that maca supplementation might improve sperm count and motility in bulls. Since 2000, extensive research has taken place but subjects have almost exclusively been humans or rodents (Table 1). Early studies demonstrated that the alcoholic extract of maca may increase the epididymal sperm count in rats by +11% and the total sperm count by 84% in men (Gonzales et al., 2001b), whereas higher dosages had the opposite effect (Gonzales et al., 2003b). Gonzales et al. (2004) described that maca treatment of rats prevented high-altitude-induced spermatogenic disruption. Based on the early promising results in bulls mentioned, Clément et al. (2010c) performed an extensive experiment and found positive effects for maca hypocotyl powder on sperm concentration, sperm motility (Fig. 1), and the DNA fragmentation index (−24%) in supplemented peripubertal breeding bulls with marginal baseline sperm quality.

Maca is characterised by various secondary metabolites. Macaene and macamides are the most distinct among them, because they occur only in maca. Maca also contains campesterol and β-sitosterol, the most common

Table 1
Experimental findings on the effects of maca hypocotyls (of different colour) on male fertility.

Form of maca	Dose	Period	Type of improvement	Species	Reference
Lipid extract	(i) 40 mg/g BW[a] (ii) 4 g/kg BW (iii) 45/180/1800 mg/kg BW	(i) 22 days (ii) 1 day (iii) 20 days	(i) Number of intromissions (ii) Number of sperm-positive females after mating (iii) Reduction of latent period of erection of testes-removed rats to that of normal rats	Mouse, rat	Zheng et al. (2000)
Aqueous extract	66.7 mg twice a day	2 weeks	Increased weights of testis and epididymis, increased length and frequency of stages IX–XIV of seminiferous tubules	Rat	Gonzales et al. (2001a)
Gelatinised maca	1500/3000 mg/day (approx 20–40 mg/kg BW and day)	4 months	Increased seminal volumen, sperm count per ejaculate, motile sperm count and sperm motility	Man	Gonzales et al. (2001b)
Gelatinised maca	1500/3000 mg/day (approx 20–40 mg/kg BW and day)	12 weeks	No effect on serum levels of reproductive hormones	Man	Gonzales et al. (2003a)
Alcoholic extract	48/96 mg/day	3 weeks	Activation of onset and progression of spermatogenesis at both doses	Rat	Gonzales et al. (2003b)
Aqueous extract	6.6/66.7/666.6 mg/day	3 weeks	Prevents high altitude-induced spermatogtenic disruption	Rat	Gonzales et al. (2004)
Aqueaous extract	66.6 mg/day	7/14/21 days	Enhances spermatogenesis following spermatogenic damage caused by an organophosphorous pesticide	Mouse	Bustos-Obregón et al. (2005)
Aqueous lyophilised extract	10/100/1000/5000 mg/kg BW	1 week	Best response in spermatogenesis with 1000 mg/kg BW	Rat	Chung et al. (2005)
Aqueous extract[b]	1.66 g/kg BW	1 or 6 weeks	Increased sperm count and epidydimal sperm motility with black maca	Rat	Gonzales et al. (2006a)
Aqueous extract of black hypocotyls	2 g/kg BW	12 days	Increased sperm count after one treatment but unclear tendency over the entire treatment period	Rat	Gonzales et al. (2006b)
Aqueous extract	2 ml/kg BW	17 days	Reduced adverse effect on daily sperm production caused by lead acetate	Rat	Rubio et al. (2006)
Aqueous extract[b]	1 g/kg body weight	12 weeks	Increased epididymal sperm count and sperm count in *Vas deferens* with black and yellow maca	Rat	Gasco et al. (2007)
Different fractions of hydroalcoholic extract of black hypocotyls	1 g/kg BW	1 week	Best response in the spermatogenesis with the ethylacetate fraction	Rat	Yucra et al. (2008)
Maca flour	233 mg/kg BW	10 weeks	Increased sperm count of peripubertal bulls; higher sperm motility and lower %DNA fragmentation index of bulls with borderline sperm quality	Cattle	Clément et al. (2010c)

[a] Body weight.
[b] Black, red and yellow hypocotyls.

phytosterols, macaridine, lepilidines, and a range of glucosinolates. Not all of these compounds are considered favourable for sperm quantity and quality. Still, some of these secondary metabolites, or distinct combinations of them, may explain the sperm production and quality enhancing effects of maca. Clear antagonisms among maca ecotypes with differently coloured hypocotyls are evident with respect to the concentrations of glucosinolates on one hand and the concentrations of macaene and macamides on the other (Clément et al., 2010a,b). This would explain why maca with hypocotyls of different colours appear to differ in their effects, with black maca being superior to reddish and yellow maca in promoting spermatogenesis (Gonzales et al., 2006a; Gasco et al., 2007). Still, the active principle(s) has to be found.

3.2. *Catha edulis* Forsk (khat)

Khat is an evergreen shrub of the Celastraceae family that mainly grows wild. It is cultivated as a cash crop in Eastern Africa (Mekasha et al., 2007) and in the Southern part of the Arabic peninsula (Nyongesa et al., 2008). The fresh leaves and the young shoots contain the monoamine alkaloid cathinone [S-(−)-α-aminopropiophenone], which has euphoric and psychoactive effects (Nyongesa et al., 2008). Cathinone is unstable, and through the plant material drying process it is metabolized relatively quickly to either cathine [S,S-(+)-pseudonorephedrine] or norephedrine [R,S-(−) norephedrine], both phenylpropanolamines. The three compounds mentioned are related to the amphetamines, but cathine and norephedrine are less potent than cathinone in this respect (Griffiths et al., 1997). This explains why dried leaves have fewer psychoactive effects than fresh leaves. Besides these compounds, khat contains more than 40 alkaloids, glycosides, tannins, and terpenoids (Nyongesa et al., 2007). In 1964, the WHO classified khat as a substance at risk for abuse as it can produce mild to moderate psychological dependence.

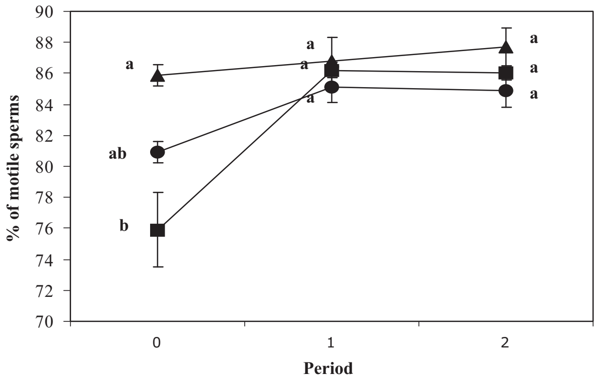

Fig. 1. Effect of maca supplementation on the visually determined motility of fresh sperm from bulls with initially borderline quality. Control bulls (●) did not receive maca at all, 'maca early' bulls (■) received maca in Period 1 and 'maca late' bulls (▲) received maca in Period 2, with Period 0 = before start of maca treatment; Period 1 = weeks 1–10; Period 2 = weeks 11–20. Unequal superscripts are different at $P < 0.05$.
Adapted from Clément et al. (2010c).

At first Islam et al. (1990) and Tariq et al. (1990) described adverse effects from khat supplementation such as decreases in sperm count and motility by 28 and 22%, respectively, a 1.53-fold increase in the number of abnormal sperm, and a 50% decrease in plasma testosterone. These authors associated the effects with cathinone. However, various subsequent studies showed positive, or a combination of positive and negative, effects from khat supplementation on sexual hormone levels, sperm morphology, and sperm activity (Table 2). Adeoya-Osiguwa and Fraser (2005, 2007) demonstrated that, at appropriate doses, cathine and norepherdrine might accelerate capacitation and inhibit spontaneous acrosome loss of sperm. Accordingly, cathine might enhance the success of *in vitro* fertilization (Adeoya-Osiguwa and Fraser, 2007). Mekasha et al. (2007, 2008) described the effects of supplementation and exclusive feeding of discarded parts of plants, leaves and stems of khat (leftovers) when marketed as cash crop where the central soft part of the leaf is sold. Both strategies enhanced scrotal circumference (11–19%), semen production (no data given), sperm motility (+60 to 75%), and sperm morphology of Ogaden bucks. Khat-supplemented olive baboons expressed a significant increase by 35% in levels of testosterone and a decrease by 36% in blood plasma levels of cortisol (Mwenda et al., 2006). Nyongesa et al. (2007) concluded that low levels of khat stimulated testosterone production by mouse interstitial cells while the opposite was the case at high khat levels. Furthermore, moderate khat supply decreased levels of the luteinizing hormone and increased cortisol levels in blood plasma (Nyongesa et al., 2008). The same researchers found that supplementation of an extract prepared from fresh khat reduced plasma luteinizing hormone levels by 24% and testosterone levels by 23%, but at the same time increased plasma cortisol levels in a dose–response type manner in male rabbits. Khat certainly warrants further studies before it can be recommended as a supplement for male breeding livestock. Rules preventing its misuse as a drug will also have to be established.

Table 2
Experimental findings on the effects of khat leaves and khat constituents on different traits of male fertility.

Supplement	Dose	Period	Effect	Species	Reference
(−)-Cathinone enantiomers	5/10/30 mg/kg body weight	15 days	Decreased sperm count, motility and plasma testosterone level, increased number of abnormal sperms, atrophy of Leydig and Sertoli cells	Rat (Wistar)	Islam et al. (1990)
(−)-Cathinone	5/10/30 mg/kg body weight	15 days	Decreased sperm count, motility, plasma testosterone level, water and food consumption and weight gain; increased number of abnormal sperms	Rat (Wistar)	Tariq et al. (1990)
Cathine, norephedrine	0.01/0.1/1/10 µmol/l	30 min 90 + 30 min	Accelerated capacitation of sperms, inhibited spontaneous acrosome reaction of sperms	Mouse/man (sperm suspensions)	Adeoya-Osiguwa and Fraser (2005)
Aqueous extract	50 ml extract once a week	>2 months	Increased plasma level of testosterone, decreased plasma levels of cortisol and prolactin	Olive baboon	Mwenda et al. (2006)
Cathine	100 nmol/l	35 min	Cathine binds to β_1-adrenergic or α_{2A}-receptors (uncapacitated/capacitated spermatozoa resp.); cathine might enhance success of *in vitro* fertilisation	Mouse (sperm suspensions)	Adeoya-Osiguwa and Fraser (2007)
Aqueous extract	0.06/0.6/6/30 ml/mg	Every 30 min during 3 h	Inhibited/stimulated testosterone production	Mouse (interstitial cells)	Nyongesa et al. (2007)
Khat leftovers	*ad libitum*/supplementation	15 weeks	Improved body weight, testicular size, semen production and sperm motility	Ogaden buck	Mekasha et al. (2007)
Khat leftovers	*ad libitum*/supplementation	15 weeks	Favourable sperm morphology	Ogaden buck	Mekasha et al. (2008)
Aqueous extract	1.5/3/6/17.5 g/ml	Every 30 min during 3 h	Reduced luteinizing hormone, increased cortisol level	Rabbit	Nyongesa et al. (2008)

3.3. *Multipurpose trees and shrubs*

Leaves of multipurpose trees and shrubs (MPT) are sometimes used as animal feed complementing nutrient-poor forages in the tropics and subtropics, especially during feed scarcity. As these woody forages are mostly legumes, they are good sources of protein but they often also contain high levels of bioactive secondary metabolites like saponins or tannins. Palatability, digestibility, and metabolic function may be impaired, and overdoses can even lead to death. However, when used adequately, poor semen quality in livestock may be enhanced. It seems likely that this could be simply an effect of coping with metabolic protein deficiency, but additional effects of the secondary compounds, or of their simultaneous removal, cannot be excluded. In developing recommendations, differences among accessions of the same MPT plant in content and the actual bioactivity of the specific compounds (Soliva et al., 2008; Bekele et al., 2009) have to be considered. Out of the MTP, effects on sperm number and quality in male livestock have been specifically reported for leucanea and sesbania.

3.3.1. Leucaena leucocephala/Leucaena pallida *(leucaena)*

Leucaena, represented by several species, is a leguminous fodder shrub of the fabaceae family, rich in protein, carotene, and several vitamins, and thus, potentially beneficial for semen quality. A potential drawback in the use of leucacena is its content of mimosine and dihydroyxy pyridone, the toxic metabolite of mimosine, which has been negatively related to conception rates in females (Holmes et al., 1981). Furthermore, adverse effects on the thyroid gland from mimosine have to be expected, although these could be alleviated by supplementation of extra iodine (Pattanaik et al., 2001). In order to be able to feed leucaena, the rumen of the supplemented animals has to be colonised with bacteria able to detoxify mimosine like *Synergistes jonesii* (Akingbade et al., 2002). Kaitho et al. (1998) found a higher scrotal circumference in sheep and goats (+22 and 58%, respectively) supplemented during 160 days with *L. pallida*. However, Woldesmeskel et al. (2001) described that *L. pallida* induced degenerative and necrotic lesions in the testes of the same sheep and goats. Akingbade et al. (2002) found that goats, which were previously treated with *S. jonesii* and were subsequently supplemented with *L. leucocephala*, obtained higher fertility rates after 77 days of supplementation compared to unsupplemented goats. Opposite to this result, Herbert et al. (2005) noted that a diet containing 200 g of *L. leucocephala* per kg caused mildly adverse effects on semen volume (−19%), sperm count (−24%), and seminiferous tubule diameter (−10%) of mature rabbit bucks. Dana et al. (2000a,b) found positive effects from *L. leucocephala* leaf hay supplementation on testicular size (+20 to +24%), semen volume (+1.86-fold), motility (+1.13-fold), and the percentage of morphological defective sperm (−90%) in Ethiopian highland sheep, but a similar improvement was achieved by simply feeding a concentrate containing wheat bran, noug cake and molasses. These inconsistencies in response to leucaena suggest that counterbalancing the low nutritional status of the animals is at least equally important for improving semen quality as the specific constituents of this plant.

3.3.2. Sesbania sesban *(sesbania)*

Sesbania sesban and other sesbania species are other well-known leguminous MPT, the leaves of which contain particularly high levels of saponins but also tannins. Mekoya et al. (2009a,b), supplementing *S. sesban* to the diet at levels of up to 300 g/kg, found beneficial effects on the onset of puberty (−34 days), testicular growth (+13%) and sperm count (+17%) of male sheep. Kaitho et al. (1998) also tested this plant, but their study did not show a specific increase in scrotal circumference, and the subsequent analysis of testis histology (Woldesmeskel et al., 2001) showed the presence of necrosis and tubular degeneration. The authors assumed that this was due to the saponins, which were found to have spermicidal activity. Melaku et al. (2004) proposed to feed a mixture of leucaena and sesbania to dilute the respective negative effects of each of their characteristic metabolites. They tested different accessions of both MPT alone and in mixture and found that combining *S. sesban* accession 1198 and *L. leucocephala* accession 14203 enhanced live weight and scrotal circumference (+58%). However, no histological analysis was performed.

3.4. Solanum lycopersicum *(tomato)*

The skin of the tomato is rich in lycopene ($C_{40}H_{56}$), a red carotenoid pigment with known antioxidant properties. Lycopene is found in the testes and seminal plasma of male mammals and is considered to be part of the non-enzymatic defence system of the semen used to cope with oxidative stress (Palan and Naz, 1996; Gupta and Kumar, 2002; Goyal et al., 2006). The same authors found lycopene concentrations in the seminal plasma of subfertile men to be significantly lower by 55% than concentrations in fertile men. Dietary lycopene supplementation increased its concentration in the seminal plasma by 7–13% in the study of Goyal et al. (2007) and had positive effects on the concentration (+62%) and motility (+66%) of sperm from men suffering from subfertility with unknown reason (Gupta and Kumar, 2002). Ateşşahin et al. (2006) induced intra-testicular toxicity in rats with cisplatin and adriamycin, and noted a preventive and protective effect of lycopene in certain sperm characteristics (*cf.* Fig. 2). Similarly, Türk et al. (2007) found a potential preventive effect from lycopene supplementation against damage of testicular tissues and low sperm quality caused by cyclosporine A in male rats. Hekimoglu et al. (2009) showed therapeutic antioxidant effects from lycopene on motility (+54 to +91%; contralateral/ipsilateral testis) and on abnormal sperm rates (−11%; ipsilateral testis) in oxidative stress associated with situational infertility problems like testicular torsion. Sources rich in lycopene like tomato pomace, the residue of tomato processing, which is available in large amounts in tomato processing countries, would, therefore, be promising as feed for reproducing male livestock. These residues have been shown to have satisfactory palatability and feeding value (Abbeddou et al., 2011). However, before considering their application in ruminants in order to improve sperm numbers and quality, it must be determined if, and to what

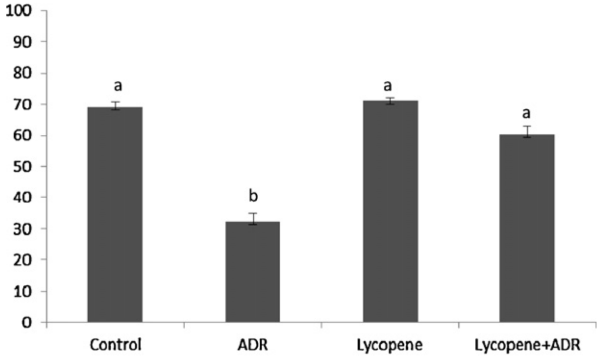

Fig. 2. Partial prevention of the adriamycin (ADR) mediated depression in motility of fresh sperm (%; visually determined) by lycopene.
Adapted from Ateşşahin et al. (2006).

extent, lycopene is able to pass the rumen undegraded. Thus far, only lycopene studies with pre-ruminant calves (Bierer et al., 1995; Sicilia et al., 2005) appear to have been conducted.

3.5. Punica granatum *(pomegranate)*

Türk et al. (2008) demonstrated that the ingestion of a high amount of pomegranate juice (1 mL/day) by adult male rats could have a beneficial effect on epididymal sperm concentration (+49%), sperm motility (+26%) and the percentage of abnormal sperms (−43%). The authors suggest that the effects are due to the increase of plasma ascorbic acid (2.9-fold of control), which is active against ROS. If ascorbic acid really explains the effect of pomegranate, this supplement is likely to be effective only in monogastric livestock, as ruminal microbes can synthesise ascorbic acid. Even in monogastrics, efficiency would have to be demonstrated clearly, as ascorbic acid is not essential to species other than primates.

3.6. Amaranthus hypochondriacus *(amaranth)*

Supplementation with amaranth (*Amaranthus hypochondriacus*), also called Prince-of-Wales-feather, an ornamental plant from Mexico, might be promising to improve sperm quantity and quality as this plant is not only a rich source of vitamins and minerals but is also characterised by a high squalene concentration (Singhal and Kulkarni, 1988). Squalene is a natural organic compound, the daily supplementation of which was shown to improve semen volume and sperm motility in boars by 33 and 28%, respectively (Zhang et al., 2008). These results await further confirmation with intact amaranth and in different livestock species.

3.7. Medicinal herbs

Many traditional medicinal plants from various locations around the world have reputations for their aphrodisiac effects. Some of them have also been tested for their effects on sperm quantity or quality or both. These studies have been conducted in humans and rodents, but not in livestock, and they are considered here only for their indicative value as most of the results still await confirmation in other studies.

Lycium barbarum is an intensely promoted Chinese medicinal herb, which is used as a traditional remedy against abnormal semen. It inhibits time- and hyperthermia-induced structural damage in murine seminiferous epithelium and delayed apoptosis in this system (Wang et al., 2002). As oxidative stress is the main cause of such degradation, many hypothesised that *L. barbarum* alleviates oxidative stress. This was confirmed by Luo et al. (2006) when they found a dose-dependent protective effect from *L. barbarum* polysaccharides against H_2O_2-induced oxidative DNA damage found in mouse testicular cells. At the same time, these polysaccharides enhanced semen quantity by 68% and sperm motility by 40% in semi-castrated rats. The water extract of the Chinese herbs *Astralagus membranaceus* (Hong et al., 1992; Liu et al., 2004) and *Acanthopanacis senticosi* (Hong et al., 1992) was shown *in vitro* to stimulate the motility of human sperm by 2.5-fold over the control. *A. membranaceus* is also a component of the traditional Japanese herbal medicine ‘Hochuekkito’, which has a reputation of improving semen quality. Lin et al. (1995) found *Magnolia officinalis*, another Chinese medicinal herb, to act in a protective manner against lipid peroxidation through its constituent magnolol, thus, facilitating sperm motility. Jeng et al. (1997) showed that the C_4-fraction of an aqueous extract of the Chinese herb *Cornus officinalis* increased human sperm motility by 0.9- to 1.2-fold (depending on the measurement technique used). Yang et al. (2008) demonstrated an increase of 23% in the sperm count of rats previously treated with cyclophosphamide when fed with *Psoralea corylifolia*, a Korean medicinal herb used to improve male reproductive function. The root of *Eurycoma longifolia* Jack, a Malaysian plant, seems promising as well. Its water-soluble extract improved sperm concentration (+54%), percentage of sperm with normal morphology (+69%), and sperm motility (+11%) in men suffering from infertility for unknown reason (Tambi and Imran, 2010). In rats, *E. longifolia* reversed the detrimental effects of oestrogen on testosterone production and spermatogenesis (Wahab et al., 2010); it also reversed the conditions of rats induced to be infertile by *Andrographis paniculata* (Chan et al., 2009). European candidate plants for improving semen quality include *Tribulus terrestris*, better known for its aphrodisiac properties. This plant was shown to promote spermatids resistant to homogenisation by 22% in a study of rats (Martino-Andrade et al., 2010). The petroleum ether extract of *Pedalium murex* also had both aphrodisiac and curative effects against ethanol-induced infertility in male rats in a Turkish study (Balamurugan et al., 2010).

4. Concluding remarks and future prospects

This review identified a rather extensive list of plant-based feed supplements with demonstrated positive effects on sperm quantity and quality, although sometimes not in farm livestock. The promising options include especially maca and khat, two tropical plants. Both are potential sources of income if grown in developing countries and marketed in industrialised countries. The overwhelming wealth of the plant kingdom is likely to provide various other effective species and substances. Future research must address potential differences between species in their response in sperm production and quality to supplementation (*cf.* Martin et al., 2010). A potential drawback in the use of dietary improvements or other means to improve semen quality lies in genetics. Bulls with originally lower semen quality will remain in the breeding programs and can widely be used in AI, thus increasing the risk of accumulating genes with adverse effects on fertility. However, fertility traits typically have rather low heritability and the potential economic gain associated with being able to maintain genotypes with a particularly high breeding value might outweigh this disadvantage.

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