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REVIEW

REVISED Phytochemicals With Anti 5-alpha-reductase Activity: A Prospective For Prostate Cancer Treatment [version 2; peer review: 1 approved, 1 approved with reservations]

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Abstract

Prostate cancer (CaP) is one of the leading causes of death in men worldwide. Much attention has been given on its prevention and treatment strategies, including targeting the regulation of 5-alpha-Reductase (5αR) enzyme activity, aimed to limit the progression of CaP by inhibiting the conversion of potent androgen dihydrotestosterone from testosterone that is thought to play a role in pathogenesis of CaP, by using the 5-alpha-Reductase inhibitors (5αRis) such as finasteride and dutasteride. However, 5αRis are reported to exhibit numerous adverse side effects, for instance erectile dysfunction, ejaculatory dysfunction and loss of libido. This has led to a surge of interests on plant-derived alternatives that might offer favourable side effects and less toxic profiles. Phytochemicals from plants are shown to exhibit numerous medicinal properties in various studies targeting many major illnesses including CaP. Therefore, in this review, we aim to discuss on the use of phytochemicals namely phytosterols, polyphenols and fatty acids, found in various plants with proven anti-CaP properties, as an alternative herbal CaP medicines as well as to outline their inhibitory activities on 5αRs isozymes based on their structural similarities with current 5αRis as part of CaP treatment approaches.

Keywords

5-alpha-reductase, Testosterone, Dihydrotestosterone, Finasteride, Dutasteride, Phytochemicals, Phytosterols, Polyphenols, Androgens, Prostate cancer

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Any reports and responses or comments on the article can be found at the end of the article.

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REVISED Amendments from Version 1

Reply to the comments made by the Reviewer:

Thank you for reviewing and suggesting some constructive amendments to the review article.

Following are the actions taken in response to the reviewer's comments. The reviewer could be able to see all the changes made to the article in response to the comments by downloading/reviewing the latest version of the review article.

- The comments made by the reviewer in Paragraph-3 (under subtopic *Inhibition of 5αRs using 5-alpha-Reductase inhibitors*) regarding the clarity of certain phrase has now been addressed and rewritten in a simpler way.

Detail: "limiting the production of androgen" changed to "reducing the production of androgen"

- Similarly in Paragraph-4 (under subtopic *Plants as an alternative to conventional 5αRs*) regarding the complexity of written text has also been addressed and now it has been rewritten in shorter sentences in a simple language suitable for the understanding of general readers.
- The comments made by the reviewer in Paragraph-5 (under subtopic *5αR inhibition activity by phytochemicals*) regarding the few typo mistakes while addressing some genus and species names, and the use of italic font has been addressed and all the correction has been made.

Detail: *Sebastiana Adenophora* changed to *Sebastiana adenophora* and *Quercus acutissima* changed to *Quercus acutissima* in-text, *Prunus Africana* changed to *Prunus africana* in Table 1 and in-text, and *Cocoz Nucifera* changed to *Cocos nucifera* in Table 1.

- The comments made by the reviewer in the discussion part regarding the simplification of the written text by breaking down the text in smaller sentences, for the understanding of general readers has been addressed.

Any further responses from the reviewers can be found at the end of the article

Introduction

Prostate cancer (CaP) is the second most deadly malignancy in men after lung cancer and the fifth leading cause of death

worldwide, accounting for 7.1% (1,276,106) of the new cases and 3.8% (358,989) of total death in males in 2018 (Rawla, 2019). According to the United Kingdom Cancer Research Centre, over 47,500 men are diagnosed with CaP each year, where one man dies from it every 45 minutes. CaP is also estimated to be the most common cancer by 2030, as one in eight men destined to be diagnosed with CaP in their lifetime. CaP is a malignant tumour that is caused by unregulated prostate cell division resulting in an abnormal cellular growth that leads to a potential spread of cancer to other body parts (Ochwang'i et al., 2014; Packer & Maitland, 2016). The current primary treatments for CaP are surgery, radiation therapy, proton beam therapy, chemotherapy, cryosurgery, high intensity focused ultra-sound and hormonal therapy, depending on the clinical conditions, outcomes and disease progression among others (Chen & Zhao, 2013). The latter strategy was largely anticipated, considering CaP as being hormones-driven disease especially during the initial stage (Taplin et al., 1995). Therefore, targeting the hormones involved in the CaP's pathway mechanisms seems to be a potentially useful approach in developing CaP prevention and treatment strategies.

Androgens and 5-alpha-Reductase enzymes (5αRs)

The physiologic functions and pathologic conditions of the prostate are regulated by numerous hormones and growth factors. For instance, androgens are essential for prostatic development and function as well as for cells' proliferation and survival (Banerjee et al., 2018). Testosterone (T), synthesised by the Leydig cells of the testes under the control of hypothalamus and anterior pituitary gland, is the most abundant circulating androgen in males, where from it, more potent form dihydrotestosterone (DHT) is synthesised (Figure 1). The microsomal enzyme 5αR mediates a rapid and irreversible T conversion to DHT within the prostate where it then binds to androgen receptor (AR) to exert its biological function (Azzouni et al., 2012). 5αR exists in two isoforms, namely type 1 (5αR1) and type 2 (5αR2), which differ in their molecular genetics, structural and biochemical properties, and tissue localisation (Nahata, 2017). 5αR1 occurs predominantly in non-genital skin, the scalp, the sebaceous gland, the liver, the kidney and the brain, whereas 5αR2 is found extensively in the prostate, genital skin, seminal vesicles and in the dermal papilla (Nahata, 2017; Othonos & Tomlinson, 2019; Strauss & FitzGerald, 2019). Both isozymes are expressed at a much lower level in other peripheral

Figure 1. The conversion of dihydrotestosterone from testosterone by 5-alpha-Reductase. The figure is adapted and modified from National Center for Biotechnology Information (2020).

tissues. Due to the tissue specific expression of 5 α Rs, DHT concentration is much higher than T concentration in the prostate. Androgens, although necessary for the development of prostate, could also allow CaP cells to grow. They promote the growth of cancerous prostate cells by binding to and activating the AR, resulting in the expression of specific genes responsible for the proliferation of CaP cells. Augmented levels of androgens, particularly DHT, are detrimental towards CaP later in life.

Inhibition of 5 α Rs using 5-alpha-Reductase inhibitors (5 α Ris)

Progression of cancer in prostate is typically dependent on the levels of androgens present during the initial stages of cancer growth (Taplin *et al.*, 1995). Therefore, reducing the production of androgen provides a useful approach to androgen deprivation where it restricts the availability of T, allowing minimal conversion to DHT by 5 α Rs and androgen-receptor binding activity. The inhibition of 5 α Rs will subsequently limit the production of DHT and therefore represents a valid target for CaP risk prevention and reduction as well as treatment strategies as a whole.

Synthetic 5 α R inhibitors (5 α Ris) can be broadly classified into two categories, namely steroidal and nonsteroidal, where their development was aimed to bind to 5 α R with little or no affinity for the androgen or other steroid receptors. The most promising and well-studied 5 α Ris by far are finasteride and dutasteride. Clinical treatment with finasteride and dutasteride have shown to decrease both mean serum and intraprostatic level of DHT in CaP patients (Andriole *et al.*, 2004; Clark *et al.*, 2004; McConnell *et al.*, 1992; Span *et al.*, 1999). Finasteride is the first synthetic steroidal 5 α Ri approved for the treatment of benign prostatic hyperplasia (BPH) and male pattern baldness (Aggarwal *et al.*, 2010; Brough & Torgerson, 2017). Finasteride, a synthetic 4-azasteroid compound, is a potent competitive inhibitor of 5 α R2 that also inhibits 5 α R1 but less effectively

(Figure 2a). Finasteride has been reported to decrease LNCaP cell growth rate *in vitro* in a dose dependent manner (Bologna *et al.*, 1995). Meanwhile, dutasteride, also a synthetic 4-azasteroid compound and an approved drug for BPH treatment, is known as a dual 5 α Ri with a 45-fold more effective in inhibiting 5 α R1 and 2-fold more effective in inhibiting 5 α R2 than finasteride (Figure 2b). Dutasteride has been reported to inhibit T and DHT-induced LNCaP cell proliferation by targeting the 5 α Rs activity and displaying a more potent DHT inhibition than finasteride (Lazier *et al.*, 2004). Dual inhibition of 5 α Rs is more beneficial than selective type 2 inhibition as it suppresses the DHT level to a great extent by also preventing the type 1 mediated synthesis of DHT production.

These observations, among others, provide a strong rationale for CaP risk reduction and prevention using 5 α Ris finasteride and dutasteride, although their use as a targeting therapeutic drug continues to be widely discussed. One of the main issues that halt the progression of 5 α Ris, considered as an effective CaP therapeutic agent, is the numerous undesirable side effects including erectile dysfunction, ejaculatory dysfunction and loss of libido (Erdemir *et al.*, 2008). 5 α Ris, which are also commonly prescribed for women with hair loss, demonstrate headache, gastrointestinal discomfort and decreased libido as the most common reported side effects (Hirshburg *et al.*, 2016). Other factors include the controversy that 5 α Ris appear to only preferentially prevent low-grade cancers and now concern lingers that 5 α Ris may induce or selectively promote growth of high-grade disease (Hamilton & Freedland, 2011).

Plants as an alternative to conventional 5 α Ris

Synthetic drugs are known to have various adverse effects, hence, safer alternative drugs have been sought, focusing on herbal sources. Older people often use traditional plants as complementary and/or alternative remedies to sustain healthy life or cure diseases. Traditional plants are known to be in medicinal

Figure 2. The chemical structure of 5 α Ris; (a) Finasteride, and (b) Dutasteride. The figure is adapted and modified from National Center for Biotechnology Information (2020).

practices for treatment of various diseases since ancient times (Falodun, 2010; Leroi-Gourhan, 1975; Pan *et al.*, 2014) and the use of medicinal plants in the search of new drugs from nature has increased since then (Savithramma *et al.*, 2011). Plants contain numerous bioactive compounds for treatment of many conditions, including cancer (Mohan *et al.*, 2011). The plant kingdom is comprised of approximately 250,000 plant species and only around 10% have been studied for the treatment of different diseases (Iqbal *et al.*, 2017). Approximately 25% of the modern drugs in clinical use are derived from plants, where the majority of these drugs were discovered as a direct result of studies focusing on the isolation of active compounds from traditional plants (Calixto, 2019).

Herbal drugs, which have been increasingly used in cancer treatment, represent a rich pool of new, and interesting bioactive entities for the development of CaP therapeutic agents. This is because herbal plants exhibit favourable side effects and toxicity profiles compared to conventional chemotherapeutic agents. Therefore, the aim of this review is to discuss the use of phytochemicals found in various plants that have been proven to exhibit anti-CaP as alternative herbal CaP medicines and to focus on the types of phytochemical present in plants that exhibit inhibitory activities on 5 α R isozymes.

5 α R inhibition activity by phytochemicals

Phytochemicals are the bioactive non-nutrient plant compounds that are found present in fruits, vegetables, grains and other plant foods, where its consumption has been linked to reduction on risk of many major chronic diseases (Sathishkumar & Baskar, 2014). Six major phytochemical categories that have been identified are phenolics, alkaloids, nitrogen-containing compounds, organosulfur compounds, phytosterols and carotenoids (Liu, 2013). The surge of interest in finding new natural bioactive entities as a template for new drug discovery and/or studying existing bioactive compounds for other biological and medicinal properties has kept scientists constantly conducting more chemical studies, particularly focusing on fractionating, isolating and identifying the active compounds. Phytochemicals offer a promising array of entities that can be further formulated into complementary or alternatives to conventional medicines that are less costly and have no/less harmful side effects. Many *in vivo* and *in vitro* studies have shown anti-CaP properties of various phytochemicals via numerous pathways as well as their ability to inhibit 5 α R activity, particularly the phytosterols and phenolics, probably due to their structural similarity with the current inhibitors of 5 α Rs. Fatty acids, which differ in structure to any 5 α Ris, are also found to exhibit anti-5 α R activity. Table 1 summarises the inhibitory action of various phytochemicals on 5 α Rs.

1. Phytosterols

Plant sterols or phytosterols (PS) are bioactive components in plants with 28- or 29-carbon alcohols and double bonds at the C-5 position of the ring that resemble cholesterol in vertebrates in terms of both of their structure and function (Zaloga, 2015). More than 200 different types of phytosterols have been reported, with β -sitosterol, campesterol and stigmasterol

being the most abundant type of PS (Miras-Moreno *et al.*, 2016). The toxicity profiles of PS have shown that there are no obvious side effects after long-term feeding of PS in both animals and humans (Ling & Jones, 1995). PS play essential roles in the reduction of cholesterol in blood that eventually decrease cardiovascular morbidity, therefore are well known for their beneficial effect on cardiovascular disease risk. Katan *et al.* (2003) reported that the intake of 1–2 g of PS daily can effectively lower low-density lipoprotein cholesterol levels by 8%-12%. However, little attention was received with regard to PS on their potential in cancer aetiology, although increasing evidence of biochemical and molecular effects of PS may make them strong candidates for cancer therapeutic agents.

Being structurally similar with four rings to synthetic 5 α Ris finasteride and dutasteride, PS could stand as the strongest promising candidate for plant-derived 5 α Ris. A study by Awad *et al.* (2001) showed that β -sitosterol inhibits the growth and migration of PC-3 human CaP and slows down the growth of prostate tumour in SCID mice, which suggests an involvement of androgenic mechanism of action as CaP is dependent on androgen. An *in vitro* metabolic study in hamster prostate by Marisa Cabeza and colleagues revealed that β -sitosterol inhibits the enzymatic activity of 5 α Rs in dose-dependent manner, which therefore confirms the ability of β -sitosterol as a 5 α Ri (Cabezal *et al.*, 2003).

Another PS, stigmasterol, was reported to be associated with a reduction in common cancer risks including colon cancer, breast cancer and CaP (Bradford & Awad, 2007). Kamei *et al.* (2018) studied *Phyllanthus urinaria* where the extract was shown to suppress androgen activity of DHT in LNCaP cell lines and has inhibitory activity against 5 α Rs, of which the active bioactive compound responsible for the activity was identified as stigmasterol isolated from an activity-guided fractionation. An *in vitro* study of *Serenoa repens* extract (SPE) using baculovirus-directed insect cell expression system demonstrated the inhibition of both 5 α R1 and 5 α R2 in a non-competitive and uncompetitive manner, respectively (Iehlé *et al.*, 1995). The major active compounds from PS of SPE includes β -sitosterol and stigmasterol (Suzuki *et al.*, 2009). SPE, a well-known phytotherapeutic agent, most frequently used to treat lower urinary tract symptoms and as a BPH medicine, not only targets the regulation of 5 α Rs activity but also hampers the binding of DHT to androgenic receptors (Dawid-Pač *et al.*, 2014). Pais (2010) reported in his study that in a cell-free test system, ethanolic extract of *Serenoa repens* was a potent inhibitor of 5 α R2 with 61% inhibition. From these observations, β -sitosterol and stigmasterol are found to exhibit inhibitory activity on both isozymes of 5 α Rs. Various plants reported to have β -sitosterol as their major active compound include *Hypoxis rooperi* extract (Harzol®), *Secale cereal* (Rye Grass Pollen), *Urtica dioica* and *Prunus Africana* (Komakech *et al.*, 2017; Madersbacher *et al.*, 2007). A study by Nahata & Dixit (2014) analysing the inhibitory effects of different types of *Urtica dioica* extracts on the activity of 5 α R2, demonstrated that ethanolic extracts were the best 5 α Ris, followed by petroleum ether and aqueous extracts. Stigmasterol, with known 5 α R2 inhibitory activity, is also

Table 1. Inhibitory action of various phytochemicals on 5αRs.

Phytochemical	Structures	Effect on 5αRs	Model of Study	Source of Plant	References
Phytosterols;					
β-sitosterol		Inhibition on type I and II	In vitro	<i>Sepinoa repen</i> , <i>Hypoxis rooperi</i> , <i>Secale cereale</i> (Rye Grass Pollen), <i>Urtica dioica</i> , <i>Prunus africana</i>	(Madersbacher et al., 2007), (Pais, 2010), (Dawid-Pač et al., 2014), (Komakech et al., 2017)
Stigmasterol		Inhibition on type I and II	In vitro	<i>Sepinoa repen</i> , <i>Phyllanthus urinaria</i> , <i>Croton sublyratus</i> , <i>Ficus hirta</i> , <i>Eclipta alba</i> (L.) Hassk, <i>Eclipta prostrata</i> , <i>Parkia speciosa</i> , <i>Gypsophila oldhamiana</i> , <i>Eucalyptus globules</i> , <i>Aralia cordata</i> , <i>Emilia sonchifolia</i> , <i>Akebia quinata</i> , <i>Desmodium styracifolium</i> , <i>Heracleum rapula</i>	(Pais, 2010), (Dawid-Pač et al., 2014), (Kamei et al., 2018)
Lupeol		Inhibition on type I and II	In vitro	<i>Sepinoa repen</i> , American ginseng, Shea butter plant, <i>Tamarindus indica</i> , <i>Allanblackia monticola</i> , <i>Himatanthus succuba</i> , <i>Celastrus paniculatus</i> , <i>Zanthoxylum riedelianum</i> , <i>Leptadenia hastata</i> , <i>Crataeva nurvala</i> , <i>Bombax ceiba</i> , <i>Sebastiania adenophora</i>	(Siddique et al., 2011) (Rainer et al., 2007)
Phenolics (Polyphenols);					
Quercetin		Inhibition on type I	In vitro	<i>Morus alba</i> L., <i>Camellia chinensis</i> , <i>Allium fistulosum</i> , <i>Calamus scipionum</i> , <i>Moringa oleifera</i> , <i>Centella asiatica</i> , <i>Hypericum hircinum</i> , <i>Hypericum perforatum</i>	(Hiipakka et al., 2002), (Salvamani et al., 2014), (Yang et al., 2015), (Kashyap et al., 2019)

Phytochemical	Structures	Effect on 5αRs	Model of Study	Source of Plant	References
Myricetin		Inhibition on type I	<i>In vitro</i>	<i>Ampelopsis cantoniensis</i> , <i>Myrica cerifera</i> L., <i>Calamus scipionum</i> , <i>Chrysobalanus icaco</i> L., <i>Moringa oleifera</i> , <i>Aloe vera</i>	(Hiipakka <i>et al.</i> , 2002), (Salvamani <i>et al.</i> , 2014)
Fisetin		Inhibition on type I	<i>In vitro</i>	<i>Butea frondosa</i> , <i>Gleditsia triacanthos</i> , <i>Quebracho colorado</i> , <i>Curcuma longa</i> , <i>Rhus verniciflua</i> , <i>Acacia greggii</i> , <i>Acacia berlandieri</i>	(Hiipakka <i>et al.</i> , 2002), (Salvamani <i>et al.</i> , 2014) (Kashyap <i>et al.</i> , 2019)
Kaempferol		Inhibition on type II	<i>In vitro</i>	<i>Moringa oleifera</i> , <i>Centella asiatica</i> , <i>Euonymus alatus</i> , <i>Kaempferia galanga</i> L., <i>Ginkgo biloba</i> , <i>Equisetum</i> spp., <i>Tilia</i> spp., <i>Sophora japonica</i> , <i>propolis</i>	(Hiipakka <i>et al.</i> , 2002), (Park <i>et al.</i> , 2006)
Biochanin A		Inhibition on type II	<i>In vitro</i>	<i>Trifolium pratense</i> L., <i>Glycine max</i> , <i>Lupinus</i>	(Jlan, 2009), (Spagnuolo <i>et al.</i> , 2015), (Zhang <i>et al.</i> , 2016)
Genistein		Inhibition on type II	<i>In vitro</i>	<i>Glycine max</i> , <i>Lupinus</i>	(Jlan, 2009), (Spagnuolo <i>et al.</i> , 2015), (Zhang <i>et al.</i> , 2016)
Daidzein		Inhibition on type II	<i>In vitro</i>	<i>Glycine max</i> , <i>Lupinus</i>	(Jlan, 2009), (Spagnuolo <i>et al.</i> , 2015), (Zhang <i>et al.</i> , 2016)

Phytochemical	Structures	Effect on 5αRs	Model of Study	Source of Plant	References
Phenolics (Catechins);					
Epicatechin-gallate		Inhibition on type I	<i>In vitro</i>	<i>Camella sinensis</i> , <i>Betula pubescens</i> , <i>Betula pendula</i> , <i>Cocos nucifera</i> , fruit pulp of <i>Argania spinosa</i> , <i>Cassia fistula</i>	(Hiipakka <i>et al.</i> , 2002)
Epigallocatechin-gallate		Inhibition on type I	<i>In vitro</i>	<i>Camella sinensis</i> , <i>Betula pubescens</i> , <i>Betula pendula</i> , <i>Cocos nucifera</i> , fruit pulp of <i>Argania spinosa</i> , <i>Cassia fistula</i>	(Hiipakka <i>et al.</i> , 2002)
Fatty Acids;					
Oleic Acid		Inhibition on type I	<i>In vitro</i>	<i>Sesuvium repens</i> , <i>Helianthus annuus</i>	(Raynaud <i>et al.</i> , 2002), (Sheeba <i>et al.</i> , 2015)
Linoleic Acid		Inhibition on type I	<i>In vitro</i>	<i>Sesuvium repens</i> , <i>Prunus africana</i> , <i>Cocos nucifera</i> , <i>Helianthus annuus</i>	(Raynaud <i>et al.</i> , 2002), (de Lourdes Arruzazabala <i>et al.</i> , 2007), (Nyamai <i>et al.</i> , 2015), (Sheeba <i>et al.</i> , 2015)
Myristic Acid		Inhibition on type II	<i>In vitro</i>	<i>Sesuvium repens</i> , <i>Prunus africana</i>	(Raynaud <i>et al.</i> , 2002)
Lauric Acid		Inhibition on type I and II	<i>In vitro</i>	<i>Sesuvium repens</i> , <i>Prunus africana</i> , <i>Cocos nucifera</i>	(Raynaud <i>et al.</i> , 2002), (de Lourdes Arruzazabala <i>et al.</i> , 2007), (Nyamai <i>et al.</i> , 2015) (Komakech <i>et al.</i> , 2017)

reported to be present in various medicinal plants including *Croton sublyratus*, *Ficus hirta*, *Eclipta alba* (L.) Hassk, *Eclipta prostrata*, *Parkia speciosa*, *Gypsophila oldhamiana*, *Eucalyptus globules*, *Aralia cordata*, *Emilia sonchifolia*, *Akebia quinata*, *Desmodium styracifolium*, *Heracleum rapula* (Chaudhary *et al.*, 2011).

Lupeol, another PS, has also been shown to exhibit various pharmacological properties including anti-CaP activity (Siddique & Saleem, 2011). Siddique *et al.* (2011) demonstrated in their study that lupeol inhibited the growth of various CaP cells i.e LAPC4, LNCaP and CRPC cells, *in vitro*. Another *in vivo* study using implanted CaP cells as xenograft tumours in mice also revealed that lupeol treatment effectively halts tumour growth, which further suggests the ability of lupeol as an effective agent that can potentially inhibit the tumorigenicity of CaP cells. Lupeol has also been observed to have a striking ability to preferentially kill CaP cells while sparing normal prostate epithelial cells (Saleem *et al.*, 2005). SPE, which contains lupeol as its bioactive compound, has been shown to possess a dual 5 α Rs inhibition activity (Iehlé *et al.*, 1995; Rainer *et al.*, 2007), therefore confirming the ability of lupeol to inhibit both 5 α R1 and 5 α R2. Lupeol can also be found in other numerous medicinal plants such as American ginseng, Shea butter plant, *Tamarindus indica*, *Allanblackia monticola*, *Himatanthus sucuuba*, *Celastrus paniculatus*, *Zanthoxylum riedelianum*, *Leptadenia hastata*, *Crataeva nurvala*, *Bombax ceiba* and *Sebastiania adenophora* (Siddique & Saleem, 2011). PS, being able to exhibit dual inhibition on both isoforms of 5 α R, further strengthens its potential as the most promising candidate as plant-derived 5 α Ris.

2. Phenolics

a) Polyphenols

Polyphenols (PP) are generally subdivided into two large groups: flavonoids and non-flavonoids. For centuries, preparation containing PP-flavonoids were applied as major active components in different remedies which were used to treat different human diseases (Salvamani *et al.*, 2014). PP exert various pharmacological effects such as anti-oxidant, anti-hypertensive, anti-inflammatory and anti-thrombotic activity that can further help in promoting human health (Hollman *et al.*, 1997; Kleemann *et al.*, 2011; Manach *et al.*, 2005; Vinson *et al.*, 1995). The toxicity profiles have shown that PP exert their therapeutic effect in a dosage-dependent manner in animal studies, whereas moderate dosages of PP do not seem to elicit any adverse effects, hence indicating its beneficial effects and safe use. Conversely, at high dosages, PP might show parallel adverse effects and/or toxicity, particularly due to accumulation of high levels of PP (Silva & Pogačnik, 2020).

PP, although lacking one 'ring', exhibit a chemical structure similar to the synthetic 5 α Ris, hence representing a potential plant-derived 5 α Ris candidate. Quercetin, one of the PP-flavonoids, has a 3-OH group on its pyrone ring and is abundant in many fruits and vegetables. It has been shown to be non-toxic and possesses an anti-cancer property in various human cancer cell lines both *in vitro* and *in vivo* including CaP (Piao *et al.*, 2014). *In vitro*, quercetin exhibits significant arrest of cell cycle,

decreases cell viability, inhibits proliferation, and induces cell apoptosis especially in PC-3, LNCaP and DU-145 cell lines, whereas when used *in vivo*, growth of a CaP cell xenograft tumour was effectively halted at a selective dosage (Yang *et al.*, 2015). Another PP, myricetin, possesses an aglycone structure that has been thought to attribute strongest inhibitory effects on enzymes such as DNA polymerases and DNA topoisomerase II and hence interferes with cellular proliferation activities (Shiomi *et al.*, 2013). Myricetin has been reported to exhibit anti-tumour activity in *in vitro* (DU-145 and PC-3 cell lines) and *in vivo* (thymic nude mice) models, by promoting cell apoptosis and inhibition of cell migration and invasion (Ye *et al.*, 2018).

Another PP, fisetin, which has two aromatic rings linked via a 3-C oxygenated heterocyclic ring with four hydroxyl groups and one oxo group, has also shown remarkable anti-cancer effects in multiple *in vitro* and *in vivo* systems. Fisetin-promoted apoptotic activation was seen in DU-145, LNCaP, and PC-3 human CaP cells (Szliszka *et al.*, 2011). Khan & colleagues (2008) conducted a study to determine whether fisetin inhibits cell growth and induce apoptosis in human CaP cells, where the study revealed fisetin treatment decrease the viability of LNCaP, CWR22Rupsilon1 and PC-3 cells while exerting only minimal effects on normal prostate epithelial cells. Fisetin arrested the G₁-phase cell cycle activity in LNCaP cells and induced cell apoptosis (Khan *et al.*, 2008). A study by Szliszka *et al.* (2011) has also demonstrated fisetin's ability to enhance cytotoxicity and apoptosis in LNCaP, DU-145 and PC-3 cells. From all of the outcomes, the PP quercetin, myricetin, and fisetin present a significant role and impact towards CaP treatment strategies via numerous pathways and this includes targeting the inhibition of 5 α R activity. An extensive study conducted by Hiipakka *et al.* (2002) to determine inhibition of 5 α R using varieties of polyphenols in cell-free assay and whole-cell assay, showed that PP quercetin, myricetin and fisetin were more potent against 5 α R1 than 5 α R2 isozyme (IC₅₀ < 100 μ M) in cell-free assay but showed little or no activity in whole-cell assay. Structure-activity relationships were also examined where it appeared that the number and position of B-ring hydroxyl groups were important for inhibitory activity against 5 α R1. Many plants are reported to contain PP like quercetin, myricetin and fisetin. For example, *Camellia chinensis*, *Allium fistulosum*, *Calamus scipionum*, *Moringa oleifera*, *Centella asiatica*, *Hypericum hircinum* and *Hypericum perforatum* have been reported to have high contents of quercetin (Salvamani *et al.*, 2014). High contents of myricetin has also been reported in *Myrica cerifera* L, *Calamus scipionum*, *Chrysobalanus icaco* L, *Moringa oleifera* and *Aloe vera* (Salvamani *et al.*, 2014). While plants like *Butea frondosa*, *Gleditsia triacanthos*, *Quebracho colorado*, *Curcuma longa*, *Rhus verniciflua*, *Acacia greggii* and *Acacia berlandieri* are rich sources of fisetin (Salvamani *et al.*, 2014).

Several other PP have also exhibited anti-CaP effects. The effect of the PP, genistein, daidzein, and biochanin A on the growth of LNCaP and DU-145 human CaP cell lines was studied where all except daidzein inhibited the cells growth (Peterson & Barnes, 1993). Wang & colleagues (2003) studied

the PP reduction effect on CaP cell proliferation and apoptotic resistance *in vitro* using a AT6.3 rat CaP cell line and revealed that the PP kaempferol, biochanin A, and genistein were responsible for inhibited cell proliferation in a dose-dependent manner and induced apoptotic effects, except for daidzein, which counteracted the effect (Wang *et al.*, 2003). Szliszka *et al.* (2013) in their study demonstrated that biochanin A remarkably augmented selective-cancer cell cytotoxicity and apoptosis in both LNCaP and DU-145 cell lines. Many *in vivo* and *in vitro* studies have demonstrated PP's ability as 5 α Ris in combating CaP (Evans *et al.*, 1995; Hiipakka *et al.*, 2002; Park *et al.*, 2003). Kaempferol, biochanin A and genistein were found to be more effective as inhibitors of 5 α R2 than 5 α R1 in a cell-free assay as well as significantly inhibit 5 α R2 in a whole-cell assay (Hiipakka *et al.*, 2002). A previous study has also demonstrated genistein and biochanin A as potent inhibitors of 5 α Rs, more specifically on type 2 in human genital skin fibroblasts and BPH tissue homogenates and on type 1 in prostate tissue homogenates (Evans *et al.*, 1995). A study that used isolated kaempferol from *Camellia sinensis* showed good inhibition on 5 α R2 in HEK-293 cells lines that expressed both 5 α Rs type 1 and 2 (Park *et al.*, 2006). Park *et al.* (2003) revealed that *Thuja occidentalis* semen (TOS) extract showed high inhibition activity on 5 α R2 that were expressed in HEK-293 cell lines. Previous studies have shown that TOS extracts contain PP flavonoids, which suggests a promising potential of PP as strong inhibitors of 5 α Rs (Hidehiko *et al.*, 1996). Kaempferol has been identified in many other plants including *Centella asiatica*, *Euonymus alatus*, *Kaempferia galanga* L, *Ginkgo biloba*, *Equisetum* spp., *Tilia* spp., *Sophora japonica* and *propolis* (Salvamani *et al.*, 2014). Genistein, daidzein and biochanin A which are the isoflavones that are mostly found in soybean (*Glycine max*), lupin (*Lupinus*) and red clover (*Trifolium pratense* L).

b) Catechin

Catechin is a type of PP that is found abundant especially in green tea. Two out of four major types of catechin are discussed herein, namely epigallocatechin-gallate (EGCG) and epicatechin-gallate (ECG). An *in vivo* study where PC-3 and LNCaP cell lines from tumour-induced mice was injected with EGCG revealed that within seven days the EGCG rapidly inhibited the growth and reduced the size of the CaP tumours (Liao *et al.*, 1995). Kao *et al.* (2000) found that EGCG reduces blood levels of T as well as prostate growth. Stadlbauer *et al.* (2018) studied the anti-tumour effect of ECG *in vitro* and demonstrated that the treatment of LNCaP and PC-3 cell lines using ECG inhibited cell viability in a dose-dependent manner. Both EGCG and ECG were also reported to have significant inhibitory effects on cell proliferation and induced apoptosis in DU-145 cells (Agarwal, 2000; Chung *et al.*, 2001). In regard to catechin as a 5 α Ri, a previous study using rat liver microsomes that expressed different types of 5 α Rs via retroviral expression vector pMV7 system has shown that ECG and EGCG are potent inhibitors of 5 α R1 but not of 5 α R2 (Liao & Hiipakka, 1995). A further extensive 5 α Ris study by Hiipakka *et al.* (2002) using a similar method as previous has demonstrated that ECG and EGCG were better inhibitors against 5 α R1 than 5 α R2. An *in vitro* study by Koseki *et al.* (2015) showed the reduction in DHT

conversion from T in 5 α Rs enzymatic activity in rat liver microsomes using *Quercus acutissima* extract where both EGCG and ECG were identified as being amongst the major components in the extract. Catechins are found in other plants such as *Betula pubescens*, *Betula pendula*, *Cocos nucifera*, fruit pulp of *Argania spinosa* and *Cassia fistula* (Hiipakka *et al.*, 2002).

3. Fatty acids

Fatty acids (FA) are monocarboxylic acids containing long hydrocarbon chains found naturally in various plants and in general can either be saturated or unsaturated (Jóźwiak *et al.*, 2020). Saturated FA includes myristic acid (MA) and lauric acid (LA), which are a long-chain fatty acid with a 14-carbon backbone and medium-chain fatty acid with a 12-carbon backbone, respectively. Oleic acid (OA) and linoleic acid (LNA) are mono-unsaturated omega-9 FA and poly-unsaturated omega-6 FA, respectively. Toxicity profiles of FA demonstrate positive impacts on various tissues as they generally pose no significant safety concern but have only low systemic toxicity potential (Burnett *et al.*, 2017; Karacor & Cam, 2015).

There are various studies that showed a decreased incidence of CaP with consumption of a FA-rich diet, especially from marine-derived FA, although knowledge on the effect of plant-derived FA on CaP remains limited. A clinical study that aimed to investigate the association of FA with risk of CaP in a case-control study of 209 CaP patients and 224 cancer-free men revealed that FA reduced the risk of CaP (Jackson *et al.*, 2012). In an *in vivo* study by de Lourdes Arruzazabala *et al.* (2007) that determined the effect of coconut oil (CO), which is rich in MA and LA, on uncontrolled growth of prostate gland using Sprague-Dawley rats, it was found that CO significantly reduced the prostate growth, suggesting that CO MA/LA-rich content could be attributed to the outcomes. This is further supported by a 14-day study by Babu *et al.* (2010) that showed MA/LA treatment in rats significantly inhibited prostate enlargement, and a four-week study by Patil & Yadav (2016) where treatment with MA and LA in rats led to significant reduction in prostate weight and DHT level in prostate.

An *in vitro* study showed that LA, OA and LNA showed proliferation inhibitory effect on LNCaP cell lines (Liu *et al.*, 2009). Another study also demonstrated LNA effects on CaP cell proliferation where it inhibited cell viability in PC-3 and LNCaP cell lines (Eser *et al.*, 2013). *Prunus africana* bark extracts, where amongst the major compounds identified are MA, LA and LNA, exhibit a very strong anti-androgenic activity and can prevent proliferation and kill CaP tumour cells (Nyamai *et al.*, 2015). Oils of *Cocos nucifera* and *Helianthus annuus* contains unsaturated FA, OA, and LNA as their major components (de Lourdes Arruzazabala *et al.*, 2007; Sheeba *et al.*, 2015). FA therefore represent a noteworthy contribution in both prevention and treatment of CaP through animal model and cell culture studies by mediating its effect in various pathways including via the inhibition of 5 α Rs enzymatic activity. Raynaud *et al.* (2002) conducted an extensive study on *Serenoa repens* lipido-sterolic extracts, which are mainly constituted of FA MA, LA, OA and LNA, for its inhibitory effects on 5 α R enzymatic

activity. The study determined the specificity of each FA inhibitory effect on both isozymes of 5 α R that have been cloned and expressed in the baculovirus-directed insect cell expression system *Spodoptera frugiperda* (Sf9). The results showed OA and LNA to be more potent against 5 α R1 than 5 α R2, while LA was found to be potent against both 5 α R1 and 5 α R2, whereas, the inhibitory effect of MA was found only active against type 2 and therefore, is a potent inhibitor of 5 α R2.

Discussion and conclusions

CaP is one of the leading causes of death in men worldwide (Daniyal *et al.*, 2014). Until today, various preventive and treatment strategies have been carried out to tackle the disease (Tindall & Rittmaster, 2008). The androgens, which are the modulator of prostate growth, are also thought to contribute to the pathogenesis of CaP. This in turn, has led to a surge of interest in studies that aim to block the activity of 5 α R using available synthetic inhibitors of 5 α R resulting in androgens deprivation as part of the strategies. The idea therefore represents a valid strategy for CaP prevention and treatment. However, the use of synthetic 5 α Ris such as finasteride and dutasteride as 5 α R activity-targeting CaP medicines continues to be widely discussed. 5 α Ris have been reported to have numerous adverse side effects (Erdemir *et al.*, 2008; Hirshburg *et al.*, 2016). Due to this, study interests have switched to finding a safer remedy with no/less harmful side effects by means of natural-derived entities found in plants as an alternative to synthetic 5 α Ris. Plants are constituted of numerous bioactive compounds and are proven to have various powerful medicinal properties that could contribute significantly towards a healthier life (Mohan *et al.*, 2011; Sathishkumar & Baskar, 2014).

The phytochemical PS, PP and FA are discussed in this review for their potential as CaP medicines and 5 α Ris. Numerous *in vitro* studies using different type of CaP cell lines and *in vivo* studies using xenograft/tumour-induced animal models have revealed the ability of PS, PP and FA as potential CaP medicines targeting various mechanisms including inhibiting cell proliferation, migration and invasion, as well as promoting selective tumour cell apoptosis. In addition, the ability of PS, PP and FA as potential naturally-derived 5 α Ris is also demonstrated in many studies, which further validates their exhibition of anti-5 α R enzymatic activity that can produce beneficial interference in androgen-dependent CaP progression. In terms of structural similarities to current synthetic 5 α Ris, PS that are characterised with four 'rings' stand as the most promising candidate for naturally-derived 5 α Ris and they are found to be potent against both 5 α R1 and 5 α R2. PP have also demonstrated anti-5 α R activity on both 5 α R1 and 5 α R2 despite lacking one 'ring'. FAs that exist in either saturated or unsaturated forms do not display any structural similarities to the synthetic 5 α Ris, but are also reported to have significant inhibitory effect against both 5 α Rs. All of these observations suggest a strong implication of various phytochemicals, especially PS, PP, and FA as potential CaP medicines targeting 5 α R activity. In conclusion, plants represent a reservoir of novel phytochemicals that can further provide a promising line on the development of CaP therapeutic agents, especially in targeting the inhibition of 5 α R enzymes.

Data availability

No data are associated with this article.

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Binesh Shrestha

Department of Chemical Biology and Therapeutics, Novartis Institutes For Biomedical Research, Basel, Switzerland

"*Prunus Africana*" has not been changed in-text yet and in reference as well. Please use the find command and change it.

"*Quercus acutissima*" in-text has not been changed to italics.

Others are fine. Once the above corrections are made, the article can be indexed.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Protein Biochemistry, Microbiology and Biotechnology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 25 May 2021

<https://doi.org/10.5256/f1000research.54175.r85610>

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Martin L. Read

Institute of Metabolism and Systems Research, University of Birmingham, Birmingham, UK

5-alpha-Reductase inhibitors (5αRis) used in the treatment of prostate cancer are reported to have numerous adverse side effects. Here, the authors report on plant-derived alternatives that might offer favourable side effects and less toxic profiles. In particular, the authors discuss the inhibitory activities of phytochemicals on 5αRs isozymes and their structural similarities with current 5αRis used in prostate cancer therapy. Overall, this review article is clear, follows a logical narrative, and is relatively well-written. I have a few minor suggestions:

1. There are a few minor edits below that need to be made in the abstract and introduction to improve clarity:

Abstract: "This has led to a surge of interests on plant-derived alternatives" should be "This has led to a surge of interest on plant-derived alternatives".

Abstract: "Therefore, in this review, we aim to discuss on the use of phytochemicals namely phytosterols" should be "Therefore, in this review, we aim to discuss the use of phytochemicals namely phytosterols".

Introduction: "The latter strategy was largely anticipated, considering CaP as being hormones-driven disease" should be "The latter strategy was largely anticipated, considering CaP is a hormones-driven disease".

Introduction: The authors should clarify the sentence "Testosterone (T), synthesised by the Leydig cells of the testes under the control of hypothalamus and anterior pituitary gland, is the most abundant circulating androgen in males, where from it, more potent form dihydrotestosterone (DHT) is synthesised".

2. It was unclear from Table 1 which type of phytochemical (i.e., PS, PP and FA) was the most effective at inhibiting the activity of 5αRs. Would it be possible for the authors to include some information (e.g., IC50 values or equivalent) to give an indication of the relative efficacies of the different phytochemicals in the inhibition of 5αRs (type I/II)? Information on the type of prostate cancer cell lines used in each study would also be helpful to include in Table 1.
3. The data shown in Table 1 is based on *in vitro* data. It would be useful to the readers if the authors included a second table giving an overview of how the different phytochemicals (i.e., PS, PP and FA) have been studied *in vivo* (i.e., mice models). In particular, the table should include information on the types of prostate cancer mouse models, the type of anti-cancer mechanisms investigated, outcomes, etc. The inclusion of this table would give important context on how these phytochemicals (i.e., PS, PP and FA) have been investigated *in vivo* and how much more work is needed.
4. It would be helpful if the authors provided additional context in the discussion and included a sentence on how many (if any) of the phytochemicals (i.e., PS, PP and FA) have been investigated in human clinical trials to inhibit 5αRs, and what still needs to be done in future studies.

Is the topic of the review discussed comprehensively in the context of the current

literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Endocrine Cancer, Drug Discovery, Bioinformatics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 30 Jun 2021

Sheikh Naeem Shafqat, Universiti Brunei Darussalam, Jalan Tungku Link, Gadong, Brunei

Reply to the comments made by the Reviewer:

Thank you for reviewing and suggesting some constructive amendments to the review article. Following are the actions taken in response to the reviewer's comments:

1. The comments made by the reviewer for the Abstract and Introduction to improve the clarity of certain phrases have now been addressed and rewritten as suggested.
 - Abstract: "This had led to a surge of interests on plant-derived alternatives" changed to "This had led to a surge of interest on plant-derived alternatives".
 - Abstract: "Therefore, in this review, we aim to discuss on the use of phytochemicals namely phytosterols" changed to "Therefore, in this review, we aim to discuss the use of phytochemicals namely phytosterols"
 - Introduction: "The latter strategy was largely anticipated, considering CaP as being hormones-driven disease" changed to "The latter strategy was largely anticipated, considering CaP is a hormones-driven disease".
 - Introduction: "Testosterone (T), synthesised by the Leydig cells of the testes under the control of hypothalamus and anterior pituitary gland, is the most abundant circulating androgen in males, where from it, more potent form dihydrotestosterone (DHT) is synthesised" changed to "Testosterone (T), the most abundant circulating androgen in males, is synthesised by the Leydig

cells of the testes under the control of hypothalamus and anterior pituitary gland, and can further be converted to more potent form dihydrotestosterone (DHT) by the action of enzyme 5 α R"

2. The comments for Table 1 (**now should be referred as Table 2**) regarding the unclarity due to missing of an indication of the phytochemicals' relative efficacies has been addressed where the IC₅₀ of each compound is included in the table and information on the type of cell lines used in each study is also added.
3. The suggestions made by the reviewer for the inclusion of another table highlighting the *in vivo* studies are appreciated and have been taken into consideration. We hereby added another table (**referred to now as Table 1**) that summarise the findings of anti-CaP studies of various phytochemicals, which also includes the *in vivo* studies.
4. The comments made by the reviewer in the Discussion section regarding the provision of additional context focusing on human clinical trials and future directions have now been addressed:
 - Discussion: The sentences "These findings are hoped to assist in the next stage of human clinical trials, as to date, only synthetic 5 α Ris are investigated in such setting. However, further isolation of these phytochemicals needs to be done especially from the plant sources before it can be implied in human clinical setting" is added.

Competing Interests: No competing interests were disclosed.

Reviewer Report 18 May 2021

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Binesh Shrestha

Department of Chemical Biology and Therapeutics, Novartis Institutes For Biomedical Research, Basel, Switzerland

Introduction

- Paragraph 3:
This can be simplified - e.g. in the second sentence, what does "limiting the production of androgen" mean? It would be clearer to say reduction or increase.

- Paragraph 4:
Similar is true here. The content of the whole paragraph would be easier to follow if it is written in simple forms. One easy way would be to break down long sentences into short sentences.
- Paragraph 5:
Please correct the typo mistakes of genus and species of some names - e.g. *Sebastiania* (genus starting with upper case) *adenophora* (species starting with lower case). Please correct the same in Table 1 as well for *Prunus africana* (throughout the article 3 times in Table 1 and also in text) and *Cocos nucifera*. For *Quercus acutissima* please change it to italics.

Discussion

- The third sentence starting with "The androgens, which are the.....as a part of the strategies" is very long (7 lines). Please simplify by breaking it down.

The overall content is good and comprehensive. I believe that the researchers in the field will have a short comprehensive overview reflection from this review. With the above-mentioned corrections, I would recommend this review for indexing.

Is the topic of the review discussed comprehensively in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes

Is the review written in accessible language?

Partly

Are the conclusions drawn appropriate in the context of the current research literature?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Protein Biochemistry, Microbiology and Biotechnology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 22 May 2021

Sheikh Naeem Shafqat, Universiti Brunei Darussalam, Jalan Tungku Link, Gadong, Brunei

Reply to the comments made by the Reviewer (Dr. Binesh Shrestha):

Thank you for reviewing and suggesting some constructive amendments to the review article.

Following are the actions taken in response to the reviewer's comments. The reviewer should be able to see all the changes made to the article in response to the comments by downloading/reviewing the latest version of the review article.

- The comments made by the reviewer in Paragraph 3 and Paragraph 4 regarding the complexity of written text have been addressed and now it has been rewritten in a simple language suitable for the understanding of general readers.
- The comments made by the reviewer in Paragraph 5 regarding the few typo mistakes, while addressing some genus and species names, and the use of italic font has been addressed and all the corrections have been made.
- The comments made by the reviewer in the Discussion regarding the simplification of the written text by breaking down the text into smaller sentences, for the understanding of general readers have been addressed.

Thank You,
Regards,
Dr. Naeem Shafqat (Author of the article)

Competing Interests: No competing interests were disclosed.

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