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REVIEW

Aflatoxin reduction in nuts by roasting, irradiation and fumigation: a systematic review and meta-analysis

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ABSTRACT

The present study aimed to investigate the reduction of aflatoxins as a potent hazard for human health in nuts during roasting, irradiation, and fumigation processes. A systematic search was performed in PubMed, Scopus, and ISI Web of Science on 6 April 2020 to find interventional studies assessing the effects of roasting, fumigation, and irradiation methods on total and individual aflatoxins concentration in nuts. Study-specific results were pooled by using a random-effects model. A total of 19 trials were included in the analyses. In most studies, the influence of method on aflatoxin reduction was assessed on peanuts. The results showed that the roasting method significantly reduced aflatoxin B1, B2, G1, and G2 concentrations by 46.91%, 30.66%, 40.88%, and 26.19%, respectively. Such results for the fumigation method were 20.88% and 22.56% for aflatoxin B1 and aflatoxin total, respectively. There was a 58.60% reduction in aflatoxin B1 and a 74.97% reduction in aflatoxin total concentrations in nuts following the irradiation method. The findings indicated that the evaluated processes could be influential for reducing aflatoxin levels in nuts.

KEYWORDS

Aflatoxin; fumigation; irradiation; roasting; nuts

Introduction

Aflatoxin, a secondary metabolite, could be produced in crops, foods, and feeds due to the fungi growth of the *Aspergillus* genus, mainly *A. flavus*, *A. parasiticus*, and *A. nomius* species at optimum condition of temperature and humidity (Magan and Olsen 2004; Frisvad et al. 2007; Arzandeh and Jinap 2011). According to evidences found in the literature, aflatoxins have immunotoxic, teratogenic, cytotoxic, hepatotoxic and genotoxic properties, and the intake of aflatoxin-contaminated foods may increase the risk of some cancer types, especially hepatocellular carcinoma (Bensassi et al. 2010; Smith and Groopman 2018; Theumer et al. 2018; Zhou et al. 2019).

There is a great concern for nuts as one of the main aflatoxin-contaminated foods in human diet (Magan and Olsen 2004; Luttfullah and Hussain 2011). The contamination of nuts with aflatoxin can be initiated from the field and continued or occurred during different production processes included pre-harvest, harvest, post-harvest, storage, handling, and distribution (Wilson and Payne 1994; Abdulkadar, Al-Ali, and Al-Jedah 2000; Abdolshahi et al. 2016). In this regard the implementation of good agricultural practice (GAP) and good manufacturing practice (GMP) have a sensible impact on prevention of *Aspergillus* infection and aflatoxin formation at any point of nuts production stages (Campbell, Molyneux, and Schatzki 2003).

Along the increase of public knowledge about the adverse health effects of hazards related to nuts such as mycotoxins, pesticides and heavy metals (Arabameri et al. 2020), the identification of effective detoxification-based methods to reduce aflatoxin level in foods is becoming an important public health priorities (Mahato et al. 2019; Naieni et al. 2020). However, numerous strategies have been developed in order to degrade aflatoxin or reduce its content in foodstuff (Rustom 1997; Cheraghali et al. 2007; Abdolshahi et al. 2019). The most frequent attempts used to reduce aflatoxin were classified as physical, chemical, and biological methods (Rustom 1997; Ismail et al. 2018; Rushing and Selim 2019). Among the physical methods, the investigation of thermal inactivation of aflatoxin indicated significant degradation of aflatoxin in some foods especially in different types of nuts. Furthermore roasting is a thermal process which can be done using dry heat at different temperatures (>70 °C) and varied duration of time to reduce the aflatoxin content in nuts (Ogunsanwo et al. 2004; Yazdanpanah et al. 2005). Using the irradiation is one of the other effective processes recommended in studies for reducing fungal toxins(Prado et al. 2003; Mustapha et al. 2014). Regarding chemical treatment the fumigation is a technique in which chemical gases as fumigants could not only control the living organism but also do develop for reduction of aflatoxin in nuts (Akbas and Ozdemir 2006; Lopes et al. 2018).

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To our knowledge, there is no available comprehensive review to evaluate the effects of different methods of aflatoxin reduction in nuts. Therefore, we aim to perform a systematic review and meta-analysis of interventional studies to gather available evidences regarding the effects of three predominant and applicable techniques including roasting, irradiation, and fumigation on levels of aflatoxins B1, B2, G1, G2, as well as total aflatoxin concentrations in nuts.

Methods

Search strategy

To find potentially relevant studies, we searched articles in English references in Web of Science, PubMed and Scopus, from database inception on 06 April, 2020. The following set of keywords was used for the systematic search: (aflatoxin OR mycotoxin OR mycotoxins) AND (nuts OR peanuts OR walnut OR almond OR pistachio) AND (reduction OR degradation OR detoxification). The reference lists of all relevant publications were manually searched to find potential additional articles (Supplementary material, Figure S1). The search was restricted to articles published in English.

The proposed criteria for inclusion and exclusion of articles

Two researchers (AA, AE) independently reviewed the titles and abstracts of all articles retrieved and selected those meeting the following criteria: (1) full-text article available; (2) original interventional studies evaluating the effects of fumigation, irradiation and roasting on aflatoxin concentrations; (3) interventional studies that were performed on nuts including peanuts, almond, walnut, pistachio, hazelnuts or other types of nuts; and (4) reported change in aflatoxins B1, B2, G1, G2, or total aflatoxin concentrations as the outcome of interest. The articles were excluded when they did not meet these criteria. The contradictions were resolved by consensus.

Data extraction

Two authors (AE, AA) independently and in duplicate extracted data from eligible studies. Any discrepancies were resolved through discussion to reach consensus. The obtained data of each article (study characteristics) was as follows: first author's name, country, publication year, type of nut (peanuts, walnut, almond, hazelnut or pistachio), reduction methods (fumigation, roasting, or irradiation), treatment dose, aflatoxin type (aflatoxin B1, B2, G1, G2 and total), and reported effect size.

Data synthesis and statistical analysis

The percent change and its standard error (SE) in total and individual aflatoxin concentrations were considered as the effect size. Meta-analysis was conducted if at least two studies reported effect size for the same outcome. Studies that reported percent change and its SE in aflatoxin concentrations following reduction methods, the effect size was included in meta-analysis as reported. Studies that did not report direct SE, the SE was calculated by multiplying standard deviation (SD) by $\sqrt{n}$. Based on the binomial distribution properties, the $SD = \frac{\sqrt{p(1-p)}}{n}$ formula was used to calculate the SD of the point estimates reported for p, where p was the mean of the percentages for the changes ($p = p_{before} - p_{after}$) and n was the sample size in each trial (Agresti 2018). Study specific results were pooled by using a random-effects model (DerSimonian and Laird 1986).

We assessed and reported heterogeneity quantitatively using the I^2 statistic and performed a χ^2 test for homogeneity ($P_{heterogeneity} > 0.10$). Using Cochrane Handbook guidance, I^2 statistics were interpreted as follows (0–40%: might not be important; 30–60%: may represent moderate heterogeneity; 50–90%: may represent substantial heterogeneity; 75–100%: considerable heterogeneity (Higgins et al. 2019). Potential publication bias was not checked due to low number of studies included in the analyses ($n < 10$) (Higgins 2011). We also executed fractional polynomial modeling (polynomials) to explore the dose-response effects of different reduction methods on total and individual aflatoxin concentrations in nuts. All analyses were conducted with Stata software, version 13 (Stata Corp, College Station, Texas, USA). Statistical was considered as significant at P value < 0.05.

Results

Data description

Figure S1 (Supplementary material) shows the literature search and study selection process. The initial systematic search identified 1296 potentially eligible publications. Among them, 125 publications were duplicates and other 1107 publications were not relevant based on the review of the title and abstract. Eventually, 64 publications were fully reviewed for inclusion in the meta-analysis. Finally, 19 publications provided sufficient information for the meta-analysis and were included in the analyses (Lee et al. 1969; Pluyer, Ahmed, and Wei 1987; Prado et al. 2003; Yazdanpanah et al. 2005; Akbas and Ozdemir 2006; Arzandeh and Jinap 2011; Mobeen et al. 2011; de Alencar et al. 2012; Chang et al. 2013; Garg et al. 2013; Chen et al. 2014; Vita, Rosa, and Giuseppe 2014; Jabłońska and Mańkowska 2014; Assuncao et al. 2015; Siciliano et al. 2017; Abuagela et al. 2018; Lopes et al. 2018; Pukkasorn, Ratphitagsanti, and Haruthaitanasan 2018; Farahmandfar and Tirgarian 2020). Reasons for excluding studies are described in (Figure S1, Supplementary material). List of excluded studies are presented in Table S1 (Supplementary material).

Nine articles (47%) were conducted in Asia (Iran, China, Turkey, Malaysia, Thailand, India and Pakistan); four (21%) in Brazil; three (16%) in the US and three (16%) in Italy and Poland in Europe (Table S2, Supplementary material). Four studies used fumigation method for aflatoxin reduction

(Akbas and Ozdemir 2006; de Alencar et al. 2012; Chen et al. 2014; Lopes et al. 2018), five studies used roasting method (Lee et al. 1969; Yazdanpanah et al. 2005; Arzandeh and Jinap 2011; Pukkasorn, Ratphitagsanti, and Haruthaitanasan 2018; Farahmandfar and Tirgarian 2020), and other ten studies used irradiation method (Pluyer, Ahmed, and Wei 1987; Prado et al. 2003; Mobeen et al. 2011; Chang et al. 2013; Garg et al. 2013; Vita, Rosa, and Giuseppe 2014; Jabłońska and Mańkowska 2014; Assuncao et al. 2015; Siciliano et al. 2017; Abuagela et al. 2018). Most studies (13 studies) were performed on peanuts (Lee et al. 1969; Pluyer, Ahmed, and Wei 1987; Prado et al. 2003; Arzandeh and Jinap 2011; Mobeen et al. 2011; de Alencar et al. 2012; Chang et al. 2013; Garg et al. 2013; Chen et al. 2014; Jabłońska and Mańkowska 2014; Abuagela et al. 2018; Pukkasorn, Ratphitagsanti, and Haruthaitanasan 2018; Farahmandfar and Tirgarian 2020), two studies were performed on pistachios (Yazdanpanah et al. 2005; Akbas and Ozdemir 2006), two studies were conducted on a mixture of nuts (Assuncao et al. 2015; Lopes et al. 2018), one study on almond (Vita, Rosa, and Giuseppe 2014) and one study on hazelnuts (Siciliano et al. 2017). General characteristic of the studies included in the present meta-analysis are provided in Table S2 (Supplementary material).

Effect of selected process on aflatoxin

Roasting of nuts

Aflatoxin B1. Five trials (20 study arms) were eligible for the analysis of roasting on aflatoxin B1 concentration (Lee et al. 1969; Yazdanpanah et al. 2005; Arzandeh and Jinap 2011; Pukkasorn, Ratphitagsanti, and Haruthaitanasan 2018; Farahmandfar and Tirgarian 2020). The roasting method decreased aflatoxin B1 concentration by 46.91% (CI: 34.55%, 59.28%, Figure 1A), with high evidence of between-study heterogeneity, $I^2 = 80\%$, $P_{\text{heterogeneity}} < 0.001$.

Aflatoxin B2. Combining nine study arms from three trials (Yazdanpanah et al. 2005; Arzandeh and Jinap 2011; Farahmandfar and Tirgarian 2020), we found a significant effect of roasting on aflatoxin B2 concentration by 30.66% (CI: 14.46%, 46.85%). However, there was high evidence of heterogeneity $I^2 = 76.2\%$, $P_{\text{heterogeneity}} < 0.001$ (Figure 1B)

Aflatoxin G1. Pooling 10 effect sizes from three trials (Lee et al. 1969; Arzandeh and Jinap 2011; Farahmandfar and Tirgarian 2020), we found significant effect of roasting method on aflatoxin G1 concentration by 40.80% (CI: 19.43%, 62.17%; $I^2 = 90.5\%$, $P_{\text{heterogeneity}} < 0.001$; Figure 1C)

Aflatoxin G2. Considering seven effect sizes from two trials (Arzandeh and Jinap 2011; Farahmandfar and Tirgarian 2020), the findings indicated that roasting method significantly decreased aflatoxin G2 concentrations by 26.19% (CI: 7.2%, 45.19%, $I^2 = 78.9\%$, $P_{\text{heterogeneity}} < 0.001$; Figure 1D)

Fumigation of nuts

Aflatoxin B1. Four trials (10 study arms) were included in the analysis of the effect of Fumigation on aflatoxin B1 concentration (Akbas and Ozdemir 2006; de Alencar et al. 2012; Chen et al. 2014; Lopes et al. 2018). The results showed that fumigation significantly decreased aflatoxin B1 concentrations by 20.88% (CI: 8.43%, 33.33%, Figure 2), with high heterogeneity, $I^2 = 84.8\%$, $P_{\text{heterogeneity}} < 0.001$.

Aflatoxin total. Four trials (nine study arms) were identified for the effect of fumigation on aflatoxin total concentration (Akbas and Ozdemir 2006; de Alencar et al. 2012; Chen et al. 2014; Lopes et al. 2018). The results showed that fumigation significantly decreased aflatoxin total concentrations by 22.56% (CI: 6.51%, 38.61%, Figure 2), with high heterogeneity, $I^2 = 87.4\%$, $P_{\text{heterogeneity}} < 0.001$.

Irradiation of nuts

Aflatoxin B1. Eight trials (28 study arms) were included in the analysis of the effect of irradiation on aflatoxin B1 concentration (Pluyer, Ahmed, and Wei 1987; Prado et al. 2003, Mobeen et al. 2011; Chang et al. 2013; Garg et al. 2013; Vita, Rosa, and Giuseppe 2014; Jabłońska and Mańkowska 2014; Assuncao et al. 2015). Our findings showed that irradiation had a significant reducing effect on aflatoxin B1 concentrations by 58.60% (CI: 51.85%, 65.35%; $I^2 = 96.3\%$, $P_{heterogeneity} < 0.001$; Figure 3).

Aflatoxin total. 3 trials (14 study arms) were considered eligible for the analysis of the effect of irradiation on aflatoxin total concentration (Garg et al. 2013; Siciliano et al. 2017; Abuagela et al. 2018). There was a 74.97% reduction in aflatoxin total concentration (95%CI: 71.82%, 78.12%; $I^2 = 47.2\%$, $P_{\text{heterogeneity}} = 0.026$; Figure 3) following irradiation method.

Dose-response meta-analysis

We also performed additional analyses to assess the potential dose-response effects of different reduction methods on total and individual aflatoxin concentrations. The results showed that total aflatoxin concentration decreased proportionally along with the increase of fumigation dose ($P_{\text{nonlinearity}} = 0.79$, Figure 4). The dose-response effects of roasting method on aflatoxin B1 ($P_{\text{nonlinearity}} = 0.001$) and G1 ($P_{\text{nonlinearity}} = 0.23$) concentrations are presented in Figure 5A and B, respectively.

Discussion

Regarding the high prevalence of aflatoxins in nuts, many different approaches are being developed to remove contamination to enhance the safety. This meta-analysis is a first study that focuses on three of most commonly methods that are generally applied for reduction of aflatoxins in nuts. In this systematic review, we gathered available evidence regarding the effects of three common approaches for aflatoxin reduction in nuts. The results showed that roasting,

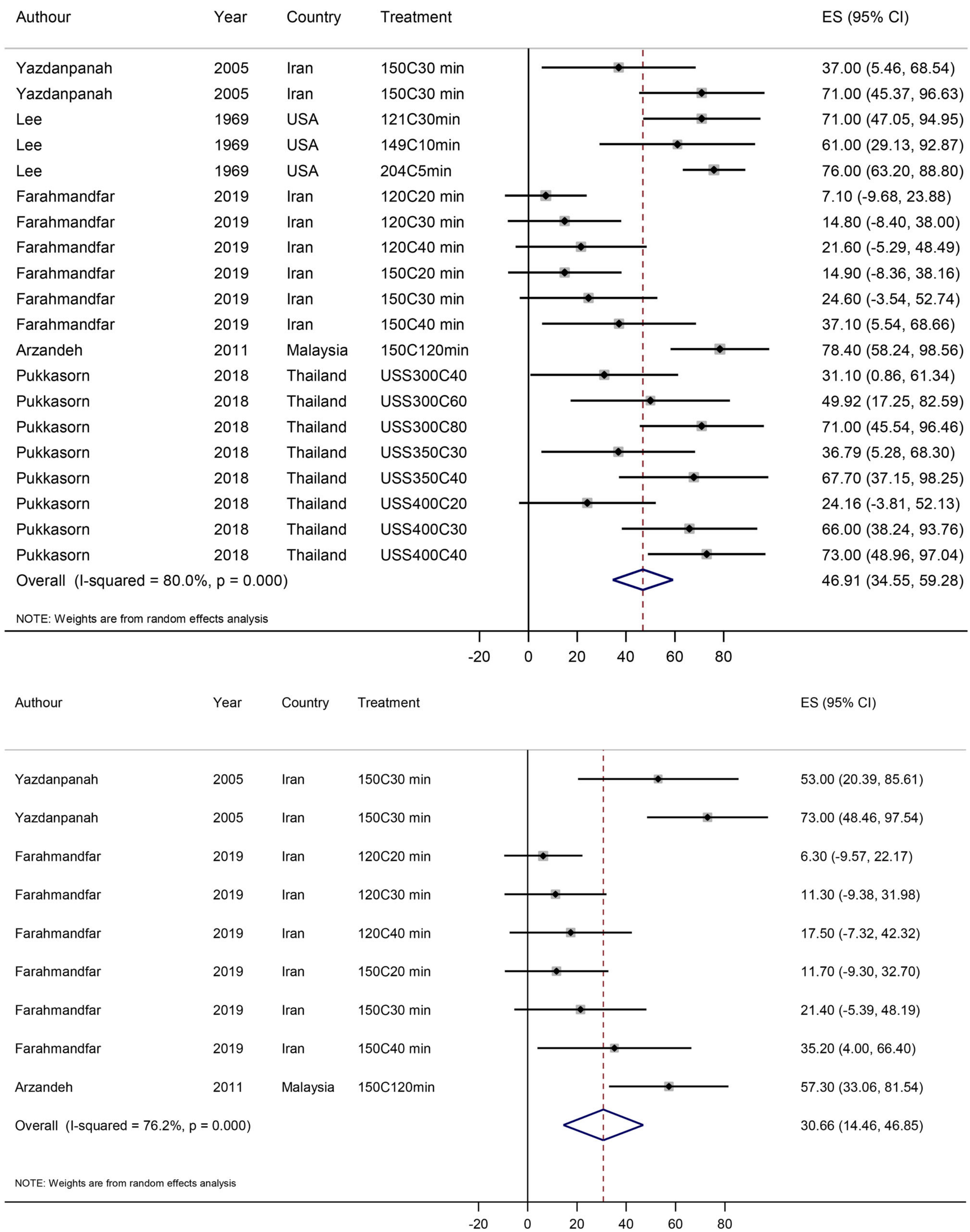
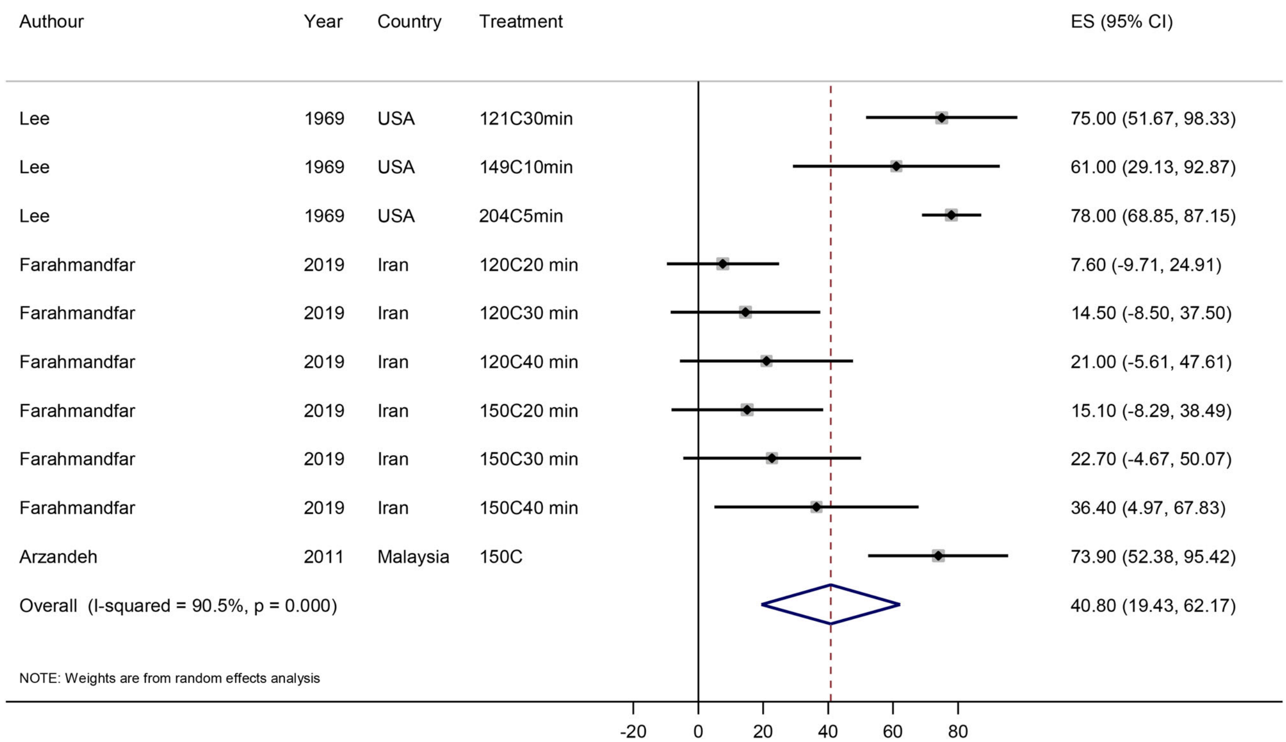


Figure 1. The effects of roasting on aflatoxin concentrations in nuts. A: aflatoxin B1; B: aflatoxin B2; C: aflatoxin G1; D: aflatoxin G2. C, centigrade; min, minute; USS, ultra-superheated steam; CI, Confidence Interval; ES, Effect size.

irradiation and fumigation processes could significantly decrease the aflatoxins concentration in different types of nuts. The reduction rates of aflatoxins strongly influenced by treatment indexes and also the initial concentration of aflatoxin and method of aflatoxin presence in nuts in terms of naturally or artificially contamination.



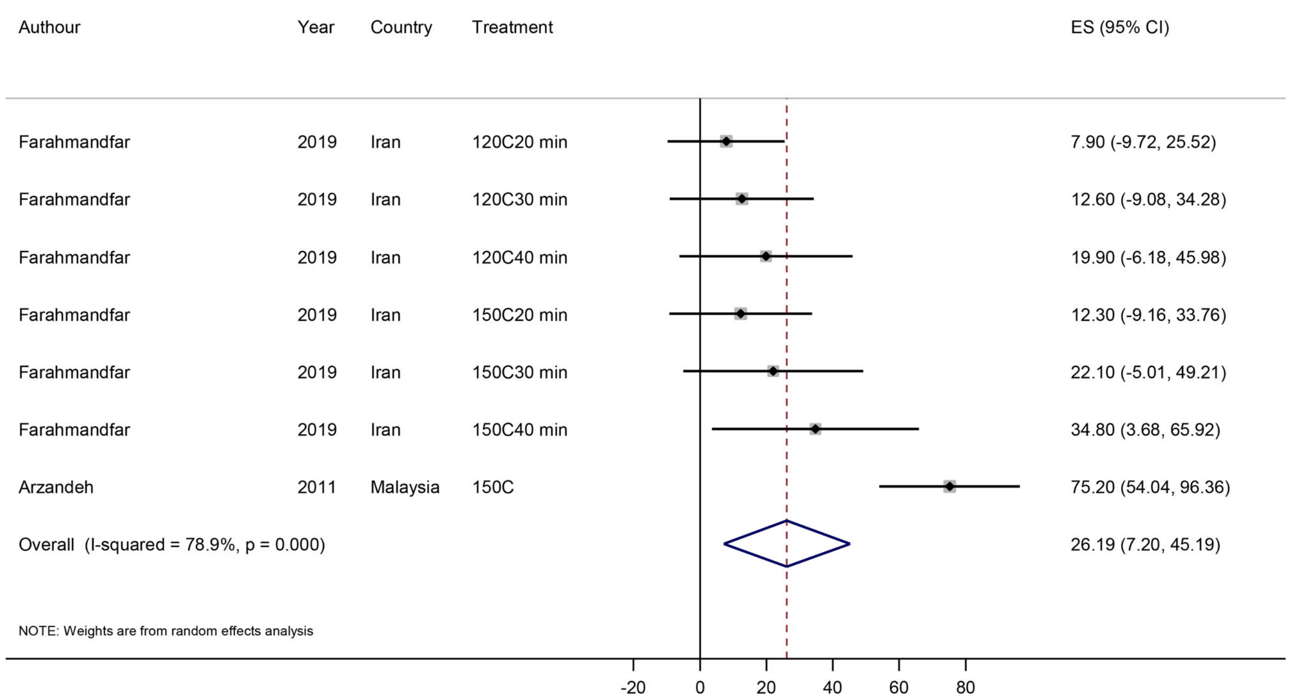


Figure 1. Cnntinued.

Reduction of aflatoxins by roasting

Roasting is one of the effective methods to reduce aflatoxins content in nuts and consequently reduce possible health risks (Ismail et al. 2018). According to the current study, roasting significantly reduced AFB1 and AFT levels in peanut and pistachio. There is a notable difference among aflatoxins degradation in term of treatment conditions. Practically decomposition of aflatoxins depended on both temperature and time (Yazdanpanah et al. 2005; Martins et al. 2017). Roasting by higher temperature at long time resulted in the most reduction effect on AFB1, AFB2, AFG1, AFG2, and AFT. However, temperature of $> 150\,^{\circ}C$ and 120 min could degrade about 95% of AFB1 in pistachio but at this condition, some physical characteristics along with sensory properties (taste and odor) will change to undesirable ones like burned state (Yazdanpanah et al. 2005). However, thermal processing of nuts like roasting is traditionally applied for biological decontaminating, and sensory

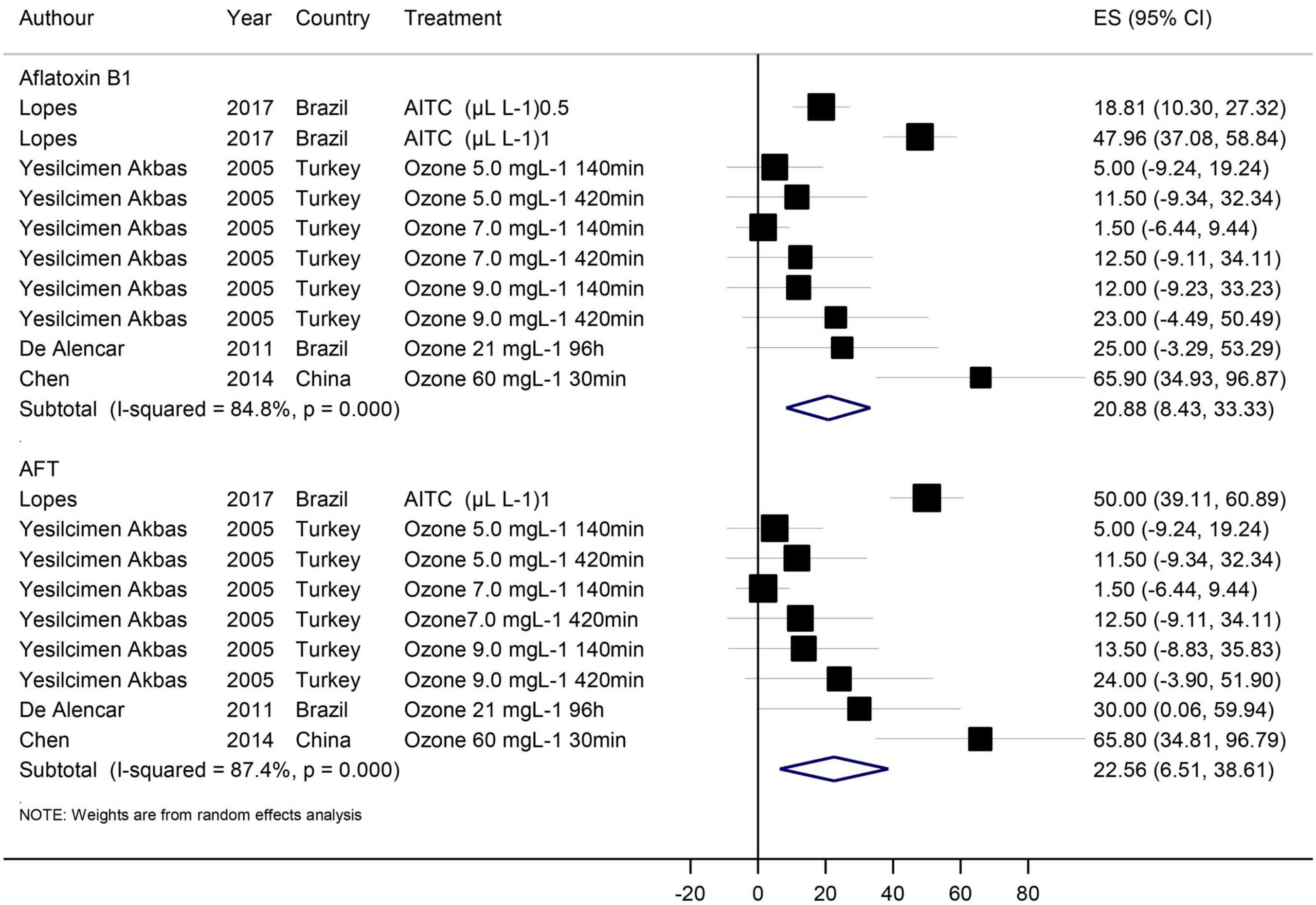


Figure 2. The effects of Fumigation on aflatoxin concentrations in nuts. (aflatoxin B1 and aflatoxin total). AITC, allyl isothiocyanate; min, minute; CI, Confidence Interval; ES, Effect size.

enhancing purposes (Khaneghah, Fakhri, and Sant'Ana 2018).

It is well known that aflatoxins have a thermal stability at high temperature so the removal of major content involves the use of harsh heating(Rushing and Selim 2019). Therefore, roasting process must be done insofar as the sensory features, nutritional values and general acceptance won't get damaged in final product. Purposed facts commonly limit the maximum usable temperature for roasting of nuts which seems degrades a part level of aflatoxins. Based on assessed studies the extent of aflatoxins reduction also depends on the initial concentration and the procedure of contamination including naturally or artificially. In an agreement manner the considered trials reported that the more initial concentration of aflatoxins increases the rate of aflatoxin reduction in nuts (Lee et al. 1969; Yazdanpanah et al. 2005; Arzandeh and Jinap 2011). Additionally, the experiment showed that aflatoxin removal in nut also depends on the method of aflatoxin contaminating of samples naturally or artificially (Lee et al. 1969; Yazdanpanah et al. 2005). For instance Yazdanpanah et al concluded that the heat resistant of aflatoxins in naturally contaminated pistachio is higher than spiked samples (even at 150 °C) (Yazdanpanah et al. 2005). Whereas in a study by Pluyer et al the reduction of AFB1 in artificially contaminated peanut (45%) was lower than naturally contaminated ones (61%)(Pluyer, Ahmed, and Wei 1987). The optimum condition of AFB1 reduction founded by Arzandeh et al for artificially contaminated peanut (initial AFB1 237 ng/g) and naturally contaminated peanut samples (174 ng/g) were 150 °C at 120 min (Arzandeh and Jinap 2011). However, the results of some studies indicated no significant difference in aflatoxin reduction between nut samples based on method of aflatoxin contamination (Arzandeh and Jinap 2011). Pukasson et al, used ultra-superheated steam (USS) as an alternative medium for transferring heat to peanut samples in order to produce roasted peanuts. They reported that high temperature (USS) abled to directly effect on peanut kernels and reduced AFB1 level (68–84%) in spiked samples at 350–450 °C during short time of thermal exposure (10–40 s) (Pukkasorn, Ratphitagsanti, and Haruthaitanasan 2018). So combined effects of temperature and time vastly influence the AFB1 decomposition in peanut kernels. Furthermore, the other indexes that might have notable effect were related to nut matrices, extraction methods, moisture content of nuts, analytical quantification techniques. Additionally it was reported that some non-aflatoxin compound might form during roasting which may react with aflatoxins and some other constituent of nuts (Ogunsanwo et al. 2004). Concerning the impact of roasting

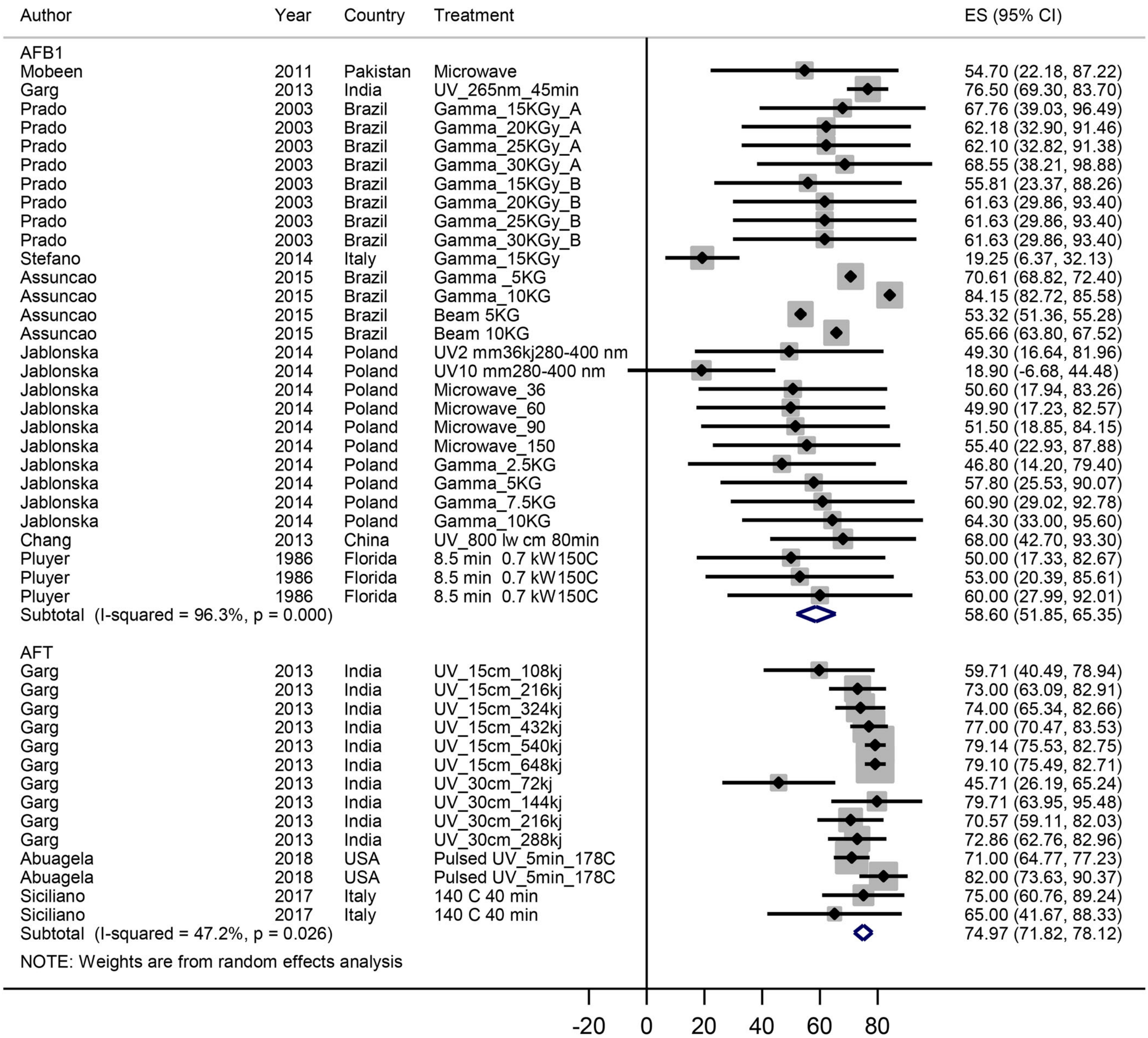


Figure 3. The effects of Irradiation on aflatoxin concentrations in nuts. (aflatoxin B1 and aflatoxin total). UV, ultraviolet; kg, kilogram; kj, kilojoule; min, minute; CI, Confidence Interval; ES, Effect size.

on aflatoxins reduction in nuts, it can evidently be accomplished easily, within short time that owing to health advantages.

Reduction of aflatoxins by irradiation

The irradiation is a physical method for decontamination of foods such as nuts that involves exposing them to radiations which classified into two categories: ionizing radiation including gamma ray, X ray or electron beams; and non-ionizing radiation including ultra violet (UV), microwaves, radio waves, infrared and visible radiation (Rustom 1997; Ismail et al. 2018; Rushing and Selim 2019). In this regard, the samples are placed in proper containers or pouches and then irradiated at definite doses of radiation at determined time and distances from the source of radiation (Ismail et al. 2018).

The evaluation of outcomes from studies indicated that most of studies had used gamma radiation, UV and microwave for aflatoxin decontamination of nuts specially peanuts. Irradiation using ionizing radiation is a process refers to penetrate the radiant energy through an object (Mustapha et al. 2014). Gamma radiation could potentially make changes in molecules of irradiated samples and no distinct changes in temperature. Based on overall knowledge the foods that treated by gamma radiation at safe doses can be recognized safe if the Good Manufacturing Practices are followed (Farag et al. 1995; De Lara et al. 2002; Prado et al. 2003). The literature review illustrated that the effect of gamma irradiation on destroying of aflatoxins in nuts is related to the amount of applied radiation (ranging from 5 to 60 KGy), the initial concentration of aflatoxins, the

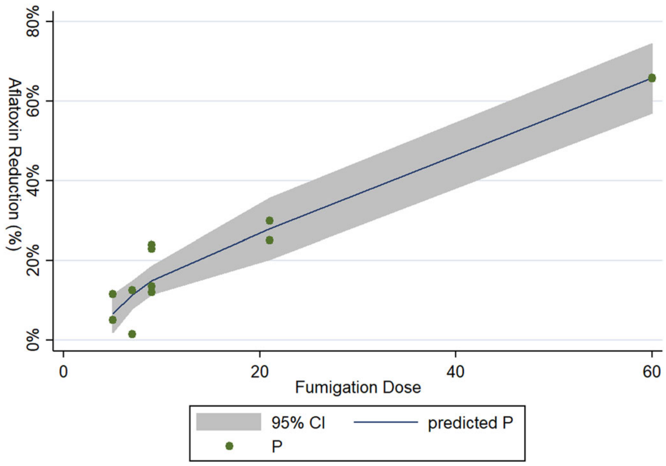


Figure 4. Dose-response effects of fumigation on total aflatoxin concentration in nuts.

moisture content, the exposure time and type of nuts (Rustom 1997; Vita, Rosa, and Giuseppe 2014; Ismail et al. 2018; Rushing and Selim 2019). Prado et al found that gamma irradiation of peanuts at 15–30 KGy degrades 55–74% of AFB1 in naturally contaminated samples. Also they reported that the final AFB1 reduction was higher in higher content of initial contamination. While Di Stefano et al reported that the percent of aflatoxins (AFB1, AFB2, AFG1, AFG2) reduction using gamma irradiation ranging from 0.5 to 15 kGy in almond samples were 0.25–21%. Additionally, the efficiency of gamma irradiation processes (5 and 10-kGy doses) in Brazil nut were 70.61% and 84.15% in Assuncao et al study. Electron beams also have been used for irradiating of Brazil nut which at doses of 5 and 10 kGy they could reduce AFB1 contents by 53.32% and 65.66% (Assuncao et al. 2015). Considering non ionizing radiation, the use of UV radiation for reducing aflatoxins has been revealed that duration of exposure and the distance of contaminated sample and UV light source were the main impressive parameter (Garg et al. 2013). The maximum reduction of AFT in Grag et al study was 99% at doses of 684 and 540 KJ/m^2 and at distance of 30 cm for exposure time of 10–12 h in peanut samples (Garg et al. 2013). The photo degradation of AFB1 on peanut by Chang et al was studied under UV irradiation (800 $\mu w/cm^2$) within 80 min exposure that could completely degrade the toxin (Chang et al. 2013). Jabłonska reported that the decrease of aflatoxins was vigorously related to thickness of nut layer exposed to UV as AFB1 reduction at 2 mm layer was 49% whereas at 11 mm layer of sample was resulted in limited UV penetration and no remarkable reduction (Jabłońska and Mańkowska 2014). The aflatoxins molecules are sensitive to absorption of UV radiation which drive to formation of some photo degradation by-products that had no significant toxicity (in vitro cytotoxicity assay) (Rustom 1997; Cardador-Martinez, Castano-Tostado, and Loarca-Pina 2002; Chang et al. 2013).

Microwave has also been applied in order to reduce aflatoxins in nuts in limited studies. Like other radiation involvements, the expose of nuts to microwave strongly depends on dose of energy and time of treatment. The reduction of aflatoxin content in the range of 36–150 KJ microwave energy in peanut was reported about 50% in Jabłonska study (Jabłońska and Mańkowska 2014). Because of that irradiation using some non-ionizing radiation such as microwave, infrared waves and visible light potentially lead to rise of the temperature at higher intensity, so it often was considered as a type of roasting or heat treatment. In another study based on microwave heating (92 °C at 5 min) the reduction percent of AFB1 after treatment of peanut and peanut product was mentioned 50–60% (Mobeen et al. 2011). Similarly microwave roasting of peanuts resulted in about 95–100% reduction in 3.2 kW for 7 min (final temperature 185 °C) (Luter, Wyslouzil, and Kashyap 1982). Irradiation method is able to reduce aflatoxin level in nuts if it accomplishes at proper condition, so it is applicable in commercial scale. Additionally there is no concerns about residual effect on environment (Luter, Wyslouzil, and Kashyap 1982; Rustom 1997; Ismail et al. 2018; Rushing and Selim 2019).

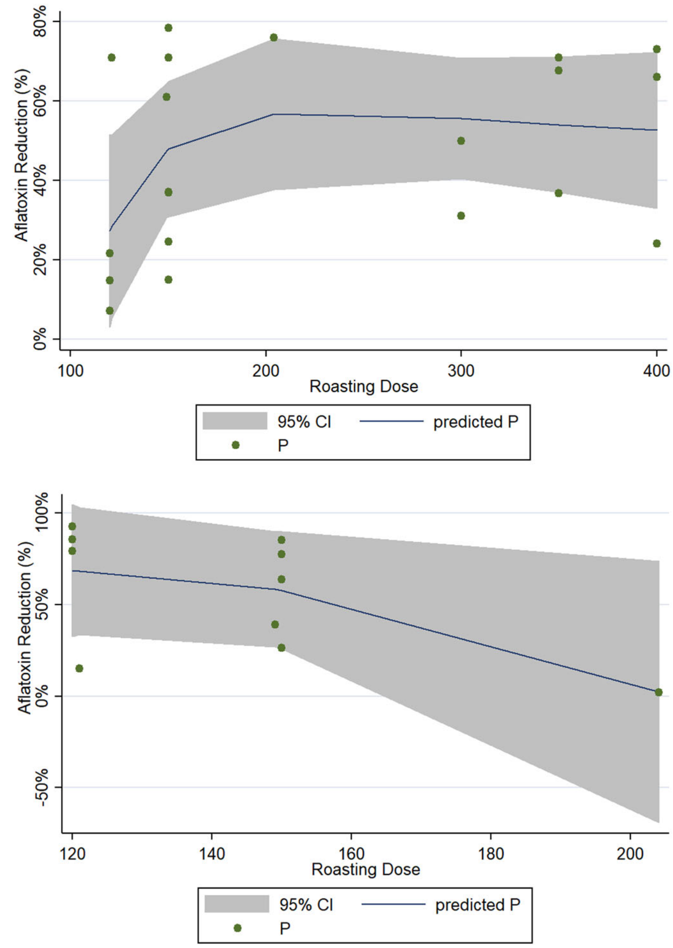


Figure 5. Dose-response effects of roasting on aflatoxin concentrations in nuts: **A**: aflatoxin B1; **B**: aflatoxin G1.

Reduction of aflatoxins by fumigation

The other efforts have been developed for preventing fungus growth and removing of aflatoxins from contaminated foods are based on chemical methods. In this way the structure of aflatoxins could be degraded via chemical agent with different activity (e.g., hydrolytic, oxidizing) and different state (liquid or gas). However despite notable effect of chemical substances on aflatoxins deactivation, majority of such strategies have no technical possibility nor economic advantages (Rustom 1997; de Alencar et al. 2012; Rushing and Selim 2019).

Many synthetic and natural chemical compounds have been assayed for inhibiting effect on fungi growth or AF removal in phosphate buffer solution but less of them proceeded to aflatoxins decontaminating effect in nuts. In addition, some introduced chemicals owing to safety risks also potential toxicity. An alternative that has been well developed for control of aflatoxins in nuts is fumigation using safe chemical gases such as ozone (Rustom 1997; Akbas and Ozdemir 2006). It is proposed that the ozonation is a technique which has a proper capability of aflatoxins and other mycotoxins degradation in nuts. Different ozone treatment in pistachio by Yesilcimen Akbas et al showed the highest reduction of AFB1 (23%) and AFT (24%) were occurred at 9.0 mg/L ozone and exposure time of 420 min by a dose and time dependent trend (Akbas and Ozdemir 2006). A study by de Alencar et al evaluated the aflatoxin detoxifying efficacy of ozone in peanut in which AFT and AFB1 reduction were 30% and 25% respectively, when ozonation performed at 21 mg/L ozone for 96 h (de Alencar et al. 2012). However, in rare studies the use of chemical agent in gaseous form were investigated on the reduction of aflatoxin in nuts. As a case, Lopes et al evaluated the fumigation of Brazil nut by means of allyl isothiocyanate (AITC) to decrease the aflatoxin contamination. The aflatoxin reduction trial with 2.5 μl/L AITC (RH = 85% and 95%) resulted in completely inhibition of AFB1, AFB2 and AFG2 (Lopes et al. 2018). The same advantage of fumigation that mentioned in all studies was the observation of no significant changes on organoleptic and nutrients of experimented nuts.

However, there are some limitations that limit the interpretation of the results. In most cases, the number of trials included in the analyses were very low, and the results were accompanied by high evidence of heterogeneity. In addition, the number of included trials was too low to test the potential for publication bias. We also have not sufficient studies to perform subgroup analyses based on dose and duration of interventions. Therefore, more trials are needed to test the effects of different reduction methods on nuts to confirm the present results.

Conclusion

The present article is the first meta-analysis study in field of reduction of aflatoxin in nuts using different processes. Based on current investigation a clear comparative data could be provided about performances of three predominant methods including roasting, irradiation and fumigation on aflatoxin destruction in nuts. Since aflatoxin has been documented as a hazard for consuming of nuts so the assessment of studies that has been focused on aflatoxin reduction indicated that the capability of some processes to degrade the aflatoxins to safe level is notable. The present meta-analysis illustrated that the content of aflatoxin could be decreased during roasting, irradiation and fumigation processes. Therefore, the implementation of these methods as preventive actions in order to reduce aflatoxins in nuts will result in reduction of the possible health risk in consumers.

Disclosure statement

The authors declare not having any conflict of interest.

Authors contributions

AA and AE designed the study, conducted systematic search and conceived screened articles and selected eligible articles, extracted information from eligible studies; AJ, and MM performed analyses and interpreted the results; AA and AE critically revised the manuscript. All authors contributed to writing, reviewing or revising the paper. AA is the guarantor. All authors have read and approved the final manuscript.

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Abbreviations

AF	Aflatoxin
AFs	Aflatoxins
AFB1	Aflatoxin B1
AFB2	Aflatoxin B2
AFG1	Aflatoxin G1
AFG2	Aflatoxin G2
AFT	Aflatoxin total
CI	Confidence Interval
SE	Standard Error
SD	Standard Deviation

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