

Effect of Carbon Nanotube Modified Epoxy Matrix on the Tensile Performance and Damage Behaviour of Flax and Jute Fabric Reinforced Composites

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Abstract

This study investigates the effect of carbon nanotube (CNT) modification of an epoxy matrix on the tensile performance and damage behaviour of flax and jute fabric reinforced composites manufactured using the resin infusion process. Multi-walled carbon nanotubes were incorporated into the epoxy matrix at different weight fractions, and composite laminates were produced with identical stacking sequences and processing conditions to enable direct comparison. Tensile properties, damage initiation behaviour and damage evolution were evaluated through tensile testing, strain mapping and acoustic emission analyses. The results show that CNT incorporation leads to significant improvements in the mechanical performance of both flax and jute reinforced composites. At an optimum CNT content of 1.0 wt.%, tensile strength increased by approximately 33% for flax composites and 32% for jute composites compared to CNT-free reference laminates. Over the same CNT range, elastic modulus values increased by 27% and 30% for flax and jute composites, respectively. Damage initiation strain values increased by 56% for flax composites and 61% for jute composites, accompanied by a reduction of 30–35% in acoustic emission event counts, indicating improved damage tolerance. Increasing the CNT content to 1.5 wt.% resulted in a reduction of tensile performance relative to the optimum CNT level, suggesting the onset of CNT agglomeration effects. Although flax reinforced composites consistently exhibited higher absolute tensile strength and stiffness than jute reinforced systems, both fibre types showed comparable relative improvements with CNT modification. When compared with conventional glass and carbon fibre reinforced epoxy composites, CNT-enhanced natural fibre composites remain lower in absolute mechanical performance; however, CNT modification significantly narrows the performance gap relative to unmodified natural fibre composites while maintaining advantages related to low density and sustainability. Overall, the findings demonstrate that CNT-modified epoxy matrices provide an effective strategy to enhance the tensile performance and damage resistance of natural fibre reinforced composites, supporting their potential use in semi-structural and sustainability-driven engineering applications.

Keywords

natural fibre composites; flax composites; jute composites; carbon nanotubes; tensile properties; damage behaviour

1. Introduction

Natural fibre reinforced polymer composites have attracted increasing attention in recent years due to growing demands for sustainability, low density and reduced environmental impact. Cellulosic fibres such as flax, jute and cotton offer significant advantages, including renewability, biodegradability, low cost and acceptable mechanical performance, making them promising alternatives for automotive components, building panels and lightweight structural applications [1–4]. However, despite these advantages, natural fibre composites still suffer from inherent drawbacks such as limited damage tolerance, weak fibre–matrix interfacial bonding and brittle failure behaviour, which restrict their wider use in load-bearing engineering applications [5–7].

To overcome these limitations, matrix modification and the incorporation of nanofillers have emerged as effective strategies for improving the mechanical performance of natural fibre reinforced composites. Among various nanofillers, carbon nanotubes (CNTs) have gained considerable interest due to their exceptionally high elastic modulus, tensile strength and large specific surface area, which enable them to act as efficient nano-scale reinforcements in polymer matrices [8, 9]. Numerous studies have

demonstrated that the addition of small amounts of CNTs into epoxy matrices can significantly enhance stiffness, strength and fracture toughness, while delaying microcrack initiation and improving load transfer mechanisms [10–12].

Most of the existing studies on CNT-reinforced composites have focused on systems reinforced with synthetic fibres such as glass and carbon fibres. In these systems, CNTs have been shown to function as nano-anchors at the fibre–matrix interface, thereby restricting crack propagation and enhancing damage resistance [13, 14]. Karahan and Godara [13] reported that CNTs, either grown on fibre surfaces or dispersed within the matrix, significantly influence damage evolution, as evidenced by acoustic emission-based damage analysis. Similarly, improvements in interlaminar shear strength (ILSS) and overall damage tolerance due to CNT incorporation have been reported for various composite systems [15].

In contrast, studies addressing the role of CNTs in natural fibre reinforced composites remain relatively limited and are often restricted to the evaluation of final mechanical properties. Zahid et al. [15] demonstrated that the incorporation of multi-walled carbon nanotubes significantly increased the ILSS of fibre reinforced composite systems. Jabbar et al. [16] and Jabbar et al. [17] reported that nanofillers and surface modification techniques can effectively improve the mechanical behaviour of natural and hybrid composite structures. Nevertheless, comprehensive investigations addressing damage initiation and damage propagation mechanisms in CNT-modified natural fibre–epoxy composites using multiple experimental techniques are still scarce in the literature.

Furthermore, the effectiveness of CNT reinforcement strongly depends on the intrinsic properties of the natural fibres used. Flax and jute fibres differ considerably in terms of chemical composition, lignin content, fibrillar structure and surface morphology, all of which directly influence fibre–matrix interfacial interactions and, consequently, the mechanical response of the composites [1, 2, 18, 19]. Koyuncu et al. [6] and Ashraf et al. [7] highlighted the role of textile architecture and reinforcement configuration on the mechanical performance of composite materials. However, systematic comparative studies investigating flax and jute reinforced composites modified with CNT-filled epoxy matrices under identical manufacturing conditions remain very limited.

In this study, the effects of carbon nanotube-filled epoxy matrices on the mechanical behaviour and damage mechanisms of flax and jute fabric reinforced composites are investigated through a comprehensive experimental approach. Composite laminates were manufactured using the resin infusion technique, and systems containing different CNT contents were compared with CNT-free reference composites. Tensile behaviour was considered as the primary mechanical performance criterion, while damage initiation and damage propagation were analysed using an integrated approach combining strain mapping, acoustic emission and microstructural observations.

In this respect, the present work aims not only to quantify the influence of CNT incorporation on the ultimate mechanical properties of natural fibre reinforced composites, but also to elucidate its role in governing the onset and evolution of damage mechanisms. The findings of this study are expected to contribute to the development of sustainable, high-performance and damage-tolerant natural fibre composite materials for engineering applications.

2. Materials and Method

2.1. Reinforcement Materials

Flax and jute woven fabrics were used as reinforcement materials in this study. Both fabrics are cellulosic natural fibres and are widely considered as sustainable alternatives to synthetic reinforcements in composite applications. Flax and jute fibres differ in terms of fibre morphology, lignin content and surface characteristics, which directly influence fibre–matrix interfacial bonding and the mechanical behaviour of the resulting composites [1–3].

The fabrics were used as received from the supplier without any chemical surface treatment to isolate the effect of carbon nanotube modification of the epoxy matrix. The basic structural and physical properties of the fabrics are summarised in Table 1.

For both fabric types, the same number of fabric layers and stacking sequence were used in all composite laminates to enable a direct comparison of the effects of fibre type and CNT content.

Table 1. Properties of the woven fabrics used in this study

Property	Flax fabric	Jute fabric
Fibre type	Flax	Jute
Weave type	Plain weave	Plain weave
Areal density (g/m ²)	280	320
Fibre density (g/cm ³)	1.45	1.46

2.2. Matrix Material and Carbon Nanotubes

A two-component epoxy resin system was used as the matrix material. Epoxy resins are commonly employed in natural fibre reinforced composites due to their good mechanical performance, low shrinkage and adequate compatibility with cellulosic fibres [4, 5].

Multi-walled carbon nanotubes (MWCNTs) were used as nano-reinforcement. Carbon nanotubes exhibit high elastic modulus, high tensile strength and large specific surface area, enabling effective load transfer and crack restriction when dispersed within polymer matrices [6-9].

Carbon nanotubes were incorporated into the epoxy resin at different weight fractions. CNT-free epoxy was used as the reference system. The CNT contents and corresponding specimen groups are presented in Table 2.

Table 2. CNT contents and specimen groups

Specimen code	CNT content (wt.%)
CNT-0	0
CNT-0.5	0.5
CNT-1.0	1.0
CNT-1.5	1.5

2.3. Resin Preparation and CNT Dispersion

Carbon nanotubes were weighed using a precision balance and gradually added to the epoxy resin. Mechanical stirring was applied to achieve preliminary dispersion of the nanotubes within the resin. The mixing process was conducted under controlled conditions to promote uniform CNT distribution.

After dispersion of the CNTs, the curing agent was added to the resin system and mixed at low speed to obtain a viscosity suitable for resin infusion. Special care was taken to minimise air entrapment during mixing. The influence of CNT agglomeration at higher CNT contents is discussed in detail in the Results and Discussion section [9, 11].

2.4. Composite Manufacturing

Composite laminates were manufactured using the resin infusion technique. This method was selected due to its ability to produce laminates with low void content, good fibre wet-out and consistent manufacturing quality, which is particularly important for natural fibre composites [12, 13].

For both flax and jute composites, eight fabric layers were used in all laminates. The stacking sequence was kept symmetric for all specimen groups. Fabric preforms were placed on the mould surface and sealed using a vacuum bagging system. The prepared epoxy/CNT resin was infused into the fabric preform under vacuum conditions.

After completion of the infusion process, the laminates were cured at room temperature followed by post-curing according to the resin manufacturer's recommendations. After curing, composite plates were demoulded and specimens were cut to the required dimensions for mechanical testing. Manufacturing parameters of the samples are given in Table 3.

2.5. Tensile Testing

Tensile tests were performed to evaluate the mechanical behaviour of the composite laminates. The tests were conducted at room temperature using a computer-controlled universal testing machine.

Specimens were prepared according to the relevant tensile testing standards. A constant crosshead speed was applied during testing. Load and displacement data were continuously recorded throughout the tests, and stress-strain curves were obtained.

Tensile strength and elastic modulus values were calculated from the stress–strain responses. For each specimen group, multiple tests were conducted to ensure repeatability, and average values were reported.

Table 3. Composite manufacturing parameters

Parameter	Value
Manufacturing method	Resin infusion
Fabric type	Flax / Jute
Number of layers	8
Stacking sequence	Symmetric
CNT contents (wt.%)	0, 0.5, 1.0, 1.5
Curing condition	Room temperature + post-cure

2.6. Damage Analysis Techniques

Damage initiation and damage propagation during tensile loading were analysed using strain mapping and acoustic emission (AE) techniques. These methods enabled real-time monitoring of damage evolution throughout the loading process.

Following the mechanical tests, fractured specimens were examined using optical microscopy to assess fibre–matrix interfacial behaviour and fracture mechanisms at the microstructural level.

3. Results and Discussions

3.1. Tensile Properties of Flax Reinforced Composites

For flax reinforced composites, the incorporation of carbon nanotubes resulted in a systematic increase in tensile strength and elastic modulus up to 1.0 wt.% CNT. Compared to the CNT-free reference composite, tensile strength increased by approximately 33%, while elastic modulus increased by 27% at 1.0 wt.% CNT.

At 1.5 wt.% CNT, both tensile strength and modulus decreased compared to the 1.0 wt.% CNT composite, indicating that excessive CNT loading does not further enhance mechanical performance. The results are given in Table 4.

Table 4. Tensile properties of flax fabric reinforced epoxy composites

CNT content (wt.%)	Tensile strength (MPa)	Standard deviation (MPa)	Elastic modulus (GPa)
0	78.4	3.2	5.6
0.5	92.7	2.8	6.4
1.0	104.3	3.1	7.1
1.5	98.9	4.0	6.8

3.2. Tensile Properties of Jute Reinforced Composites

Jute reinforced composites exhibited lower tensile strength and elastic modulus values than flax reinforced composites at all CNT contents. However, CNT modification significantly improved the tensile performance of jute composites. At 1.0 wt.% CNT, tensile strength increased by approximately 32%, while elastic modulus increased by 30% compared to the reference composite.

Similar to flax composites, a reduction in tensile properties was observed at 1.5 wt.% CNT, confirming the presence of an optimum CNT loading level. The results are given in Table 5.

Table 5. Tensile properties of jute fabric reinforced epoxy composites

CNT content (wt.%)	Tensile strength (MPa)	Standard deviation (MPa)	Elastic modulus (GPa)
0	62.1	2.9	4.3
0.5	73.6	3.4	5.0
1.0	81.8	3.0	5.6
1.5	77.2	3.7	5.3

3.3. Damage Initiation Based on Strain Mapping Results

Damage initiation strain values increased with CNT incorporation for both fibre systems, reaching a maximum at 1.0 wt.% CNT. This indicates delayed damage initiation and improved resistance to early matrix cracking. The reduction observed at 1.5 wt.% CNT supports the mechanical test results and suggests a decrease in damage tolerance at higher CNT contents. The results are given in Table 6.

Table 6. Damage initiation strain values obtained from strain mapping

Composite type	CNT content (wt.%)	Damage initiation strain (%)
Flax	0	0.82
Flax	0.5	1.05
Flax	1.0	1.28
Flax	1.5	1.12
Jute	0	0.64
Jute	0.5	0.88
Jute	1.0	1.03
Jute	1.5	0.95

3.4. Acoustic Emission Characteristics

CNT-modified composites exhibited a lower number of acoustic emission events and reduced maximum signal amplitudes compared to CNT-free composites. This behaviour indicates a transition from sudden, unstable damage to more progressive damage accumulation. The results are given in Table 7.

Table 7. Acoustic emission results for selected composite systems

Composite type	CNT content (wt.%)	Total AE event count	Maximum amplitude (dB)
Flax	0	1450	78
Flax	1.0	980	71
Jute	0	1680	82
Jute	1.0	1120	75

3.5. Integrated Discussion and Comparison with Conventional Fibre Composites

The integrated evaluation of tensile properties, damage initiation behaviour and acoustic emission results demonstrates that both fibre type and CNT content play decisive roles in determining the mechanical performance of the investigated composites.

3.5.1. Internal Comparison of Flax and Jute Composites

When flax and jute reinforced composites are compared at identical CNT contents, flax composites consistently exhibit higher tensile strength, elastic modulus and damage initiation strain (Tables 5-7). This behaviour is primarily attributed to the superior intrinsic mechanical properties of flax fibres and their more effective stress transfer capability within the epoxy matrix, as widely reported in the literature [1÷3].

Despite their lower absolute mechanical performance, jute composites display a comparable relative improvement trend with CNT incorporation. At 1.0 wt.% CNT, tensile strength increases of approximately 30÷33% are achieved for both fibre systems. This indicates that CNT-modified epoxy matrices are equally effective in enhancing load transfer efficiency in both flax and jute-based composites, regardless of differences in fibre morphology and fibre–matrix interfacial strength.

3.5.2. Effect of CNT Content Across Composite Systems

For both fibre types, an optimum CNT content of 1.0 wt.% is clearly identified. At this CNT level, maximum tensile strength, elastic modulus and damage initiation strain values are obtained, accompanied by reduced acoustic emission activity (Tables 5-7). This confirms that CNT incorporation improves not only the ultimate mechanical properties but also the damage tolerance of the composites.

At 1.5 wt.% CNT, a reduction or saturation in mechanical performance is observed for both flax and

jute composites. This behaviour is consistent with previously reported studies on CNT-modified epoxy systems, where excessive nanotube content leads to agglomeration and the formation of stress concentration sites that limit further performance enhancement [6÷9, 13].

The consistency of this trend across both fibre systems highlights that the observed optimum CNT content is governed primarily by matrix-dominated mechanisms rather than fibre-specific effects.

3.5.3. Comparison with Glass and Carbon Fibre Reinforced Epoxy Composites

When compared with conventional glass fibre reinforced epoxy composites, the tensile strength and stiffness of the investigated flax and jute composites remain lower. Typical tensile strength values for glass/epoxy composites reported in the literature range from 300 to 600 MPa, with elastic modulus values exceeding 20 GPa [14, 15]. In contrast, the natural fibre composites investigated in this study exhibit tensile strength values below 120 MPa and modulus values below 8 GPa.

However, the objective of natural fibre composite development is not to directly replace high-performance glass or carbon fibre systems, but rather to provide sustainable, lightweight and cost-effective alternatives for semi-structural applications. In this context, the relative performance enhancement achieved through CNT modification is particularly significant.

Compared to carbon fibre reinforced epoxy composites, which typically exhibit tensile strengths above 800 MPa and elastic modulus values exceeding 60 GPa [16], the performance gap is more pronounced. Nevertheless, CNT-enhanced natural fibre composites offer advantages in terms of lower density, reduced environmental impact and improved damage tolerance behaviour, as evidenced by delayed damage initiation and reduced acoustic emission activity.

3.5.4. Positioning of CNT-Enhanced Natural Fibre Composites

The results of this study position CNT-enhanced flax and jute epoxy composites between conventional natural fibre composites and traditional glass fibre reinforced systems. While they do not reach the absolute mechanical performance of synthetic fibre composites, CNT modification significantly narrows the performance gap and improves damage resistance.

These findings suggest that CNT-enhanced natural fibre composites are particularly suitable for applications where moderate mechanical performance, improved damage tolerance and sustainability are simultaneously required, such as automotive interior components, panels and secondary load-bearing structures.

4. Conclusions

This study investigated the effect of carbon nanotube modification of an epoxy matrix on the tensile performance and damage behaviour of flax and jute fabric reinforced composites manufactured by resin infusion. The results demonstrate that CNT incorporation leads to clear and quantifiable improvements in the mechanical response of both fibre systems.

The addition of carbon nanotubes resulted in tensile strength increases of approximately 33% for flax composites and 32% for jute composites at an optimum CNT content of 1.0 wt.% compared to CNT-free reference laminates. Over the same CNT range, the elastic modulus increased by 27% for flax composites and 30% for jute composites, confirming the effectiveness of CNT-modified epoxy matrices in enhancing load transfer efficiency.

Increasing the CNT content beyond the optimum level to 1.5 wt.% did not yield further improvement in tensile performance. Instead, tensile strength decreased by approximately 5–6% relative to the optimum CNT content for both flax and jute composites, indicating that excessive CNT loading adversely affects the mechanical behaviour due to agglomeration-related effects.

At identical CNT contents, flax reinforced composites consistently exhibited higher tensile strength and stiffness than jute reinforced composites. The tensile strength of flax composites was 20–25% higher than that of jute composites, while elastic modulus values were 22–30% higher across all CNT levels. Damage initiation strain values were also higher for flax composites, indicating superior resistance to early damage development.

Carbon nanotube incorporation significantly improved damage tolerance for both fibre systems.

Damage initiation strain increased by 56% for flax composites and 61% for jute composites when CNT content was increased from 0 to 1.0 wt.%. In parallel, acoustic emission event counts were reduced by 30–35%, reflecting a transition from abrupt failure to more progressive damage accumulation.

When positioned within the broader context of fibre reinforced epoxy composites, CNT-enhanced flax and jute systems remain below the absolute mechanical performance of glass and carbon fibre reinforced composites. However, compared to conventional glass/epoxy systems, the tensile strength of CNT-enhanced natural fibre composites remains approximately 70–85% lower, while the gap increases further when compared to carbon/epoxy composites. Despite this, CNT modification significantly narrows the performance gap relative to unmodified natural fibre composites and provides improved damage tolerance while maintaining the advantages of low density and sustainability.

Overall, the findings demonstrate that CNT-modified epoxy matrices provide an effective and scalable approach for enhancing the tensile performance and damage resistance of natural fibre reinforced composites. The quantified improvements reported in this study support the potential application of CNT-enhanced flax and jute composites in semi-structural, lightweight and sustainability-driven engineering applications.

References

1. Ari A., Karahan M., Ahmed H.A.M., Babiker O., Dehşet R.M.A. (2023): *A review of cellulosic natural fibers' properties and their suitability as reinforcing materials for composite panels and applications*. AATCC Journal of Research, eISSN 2330-5517, Vol. 10(3), pp. 163-183, <https://doi.org/10.1177/2472344422114736>
2. Ari A., Karahan M., Kopar M., Ahrari M., Khan R.M.W.U., Hussain M. (2023): *Comparative analysis of natural fibres characteristics as composite reinforcement*. Industria Textila, ISSN 1222-5347, Vol. 74(4), pp. 403-411, DOI:10.35530/IT.074.04.2022110
3. Pickering K.L., Efendy M.G.A., Le T.M. (2016): *A review of recent developments in natural fibre composites and their mechanical performance*. Composites Part A: Applied Science and Manufacturing, eISSN 1878-5840, Vol. 83, pp. 98-112, <https://doi.org/10.1016/j.compositesa.2015.08.038>
4. Faruk O., Bledzki A.K., Fink H.P., Sain M. (2012): *Biocomposites reinforced with natural fibers: 2000–2010*. Progress in Polymer Science, eISSN 1873-1619, Vol. 37, pp. 1552-1596, <https://doi.org/10.1016/j.progpolymsci.2012.04.003>
5. Khan M.I., Karahan M. (2022): *Testing of natural fiber composites*. Chapter 7, pp. 131-148, https://doi.org/10.1007/978-3-031-20597-2_7. In: Nawab Y., Saouab A., Imad A., Shaker K. (eds): *Natural Fibers to Composites: Process, Properties, Structures*. Springer, Cham, eISBN 978-3-031-20597-2
6. Koyuncu M., Karahan M., Karahan N., Shaker K., Nawab Y. (2016): *Static and dynamic mechanical properties of cotton/epoxy green composites*. Fibres & Textiles in Eastern Europe, eISSN 2300-7354, Vol. 4(118), pp. 105-111, DOI:10.5604/12303666.1201139
7. Ashraf W., Nawab Y., Umair M., Shaker K., Karahan M. (2017): *Investigation of mechanical behavior of woven/knitted hybrid composites*. Journal of the Textile Institute, eISSN 0040-5000, Vol. 108(9), pp. 1510-1517, <https://doi.org/10.1080/00405000.2016.1258951>
8. Thostenson E.T., Ren Z., Chou T.W. (2001): *Advances in the science and technology of carbon nanotubes and their composites*. Composites Science and Technology, eISSN 1879-1050, Vol. 61, pp. 1899-1912, [https://doi.org/10.1016/S0266-3538\(01\)00094-X](https://doi.org/10.1016/S0266-3538(01)00094-X)
9. Gojny F.H., Wichmann M.H.G., Köpke U., Fiedler B. (2004): *Carbon nanotube-reinforced epoxy-composites: Enhanced stiffness and fracture toughness at low nanotube content*. Composites Science and Technology, 64(15), ISSN: 0266-3538, pp. 2363-2371, DOI:10.1016/j.compscitech.2004.04.002
10. Allaoui A., Bai S., Cheng H.M., Bai J.B. (2002): *Mechanical and electrical properties of a MWNT/epoxy composite*. Composites Science and Technology, eISSN 1879-1050, Vol. 62(15), pp. 1993-1998, [https://doi.org/10.1016/S0266-3538\(02\)00129-X](https://doi.org/10.1016/S0266-3538(02)00129-X)
11. Karahan, M. (2012). The effect of fibre volume fraction on damage initiation and propagation of woven carbon-epoxy multi-layer composites. *Textile Research Journal*, ISSN: 0040-5175, 82(1), 45-61. <https://doi.org/10.1177/0040517511416282>
12. Lomov, S. V., Karahan, M., Bogdanovich, A. E., & Verpoest, I. (2014). Monitoring of acoustic emission damage during tensile loading of 3D woven carbon/epoxy composites. *Textile Research Journal*, ISSN: 0040-5175, 84(13), 1373-1384. <https://doi.org/10.1177/0040517513519510>
13. Karahan M., Godara A. (2013): *Influence of carbon nanotubes grown on the fibres on damage progression in woven carbon-epoxy composites*. Journal of Reinforced Plastics and Composites, eISSN 1530-7964, Vol. 32(8), pp. 515-524, <https://doi.org/10.1177/0731684413476354>

14. Lomov S.V., Beyers L., Gorbatiikh L., Verpoest I., Koysin V., Kotanjac Z., Karahan M. (2010): *Permeability and compressibility of CNT/CNF grafted reinforcements*. Proceedings of FPCM-10, <https://www.researchgate.net/publication/254860154>
15. Zahid S., Nasir M.A., Nauman S., Karahan M., Nawab Y., Ali H.M., Ullah M. (2019): *Experimental analysis of ILSS of glass fibre reinforced composites enhanced with multi-walled carbon nanotubes*. Journal of Mechanical Science and Technology, eISSN 1976-3824, Vol. 33(1), pp. 197-204, <https://doi.org/10.1007/s12206-018-1219-0>
16. Jabbar M., Karahan M., Nawab Y., Ashraf M., Hussain T. (2019): *Effect of silica nanoparticles on mechanical properties of Kevlar/epoxy hybrid composites*. Journal of the Textile Institute, eISSN 0040-5000, Vol. 110(4), pp. 606-613, <https://doi.org/10.1080/00405000.2018.1529213>
17. Jabbar A., Hussain J., Basit A., Naeem M.S., Javaid M.U., Karahan M., Nazir A. (2020): *Influence of chemical treatments and nanocellulose spray coating on the mechanical, low velocity impact and compression after impact performance of nonwoven jute composites*. Journal of Natural Fibers, eISSN 1544-046X, Vol. 17(12), pp. 1785-1797, <https://doi.org/10.1080/15440478.2019.1598918>